MODELLING THE IMPACT OF CLIMATE CHANGE ON WATER QUALITY IN THE LOWER THAMES

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ABSTRACT

There is concern as to the possible implications rising atmospheric carbon dioxide concentrations will have on the quality and quantity of water resources.

The River Network Water Quality Model, QUASAR (Quality Simulation Along Rivers) has been calibrated for the lower reaches of the Thames, from Cookham to Teddington, using data from 1974, and validated using data from 1975. Climate change scenarios were applied to data from 1974, 1975, 1976 and 1989 to assess the impact of changes in precipitation and evapotranspiration on water quality.

The model can be used in a stochastic or a dynamic mode, simulating a total of eight water quality variables in addition to flow, including dissolved oxygen, biochemical oxygen demand, nitrate, ammonia, temperature, ortho-phosphate, pH and any conservative pollutant.

Significant changes were only observed for dissolved oxygen and biochemical oxygen demand. Although there was little change in the annual mean values of these parameters, the changes in the distributions of the dissolved oxygen were sufficient in some cases to lower the water quality classification. The results of the model output suggest that under such climatic changes, investment would be needed to maintain water quality objectives and consent discharges may have to be reassessed.

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CHAPTER ONE

INTRODUCTION

Growing attention is being paid to climate changes that may result from increasing atmospheric concentrations of carbon dioxide and other trace gases. If decisions in relation to the allocation of capital and current expenditure to water resource systems are to be improved, then a clear understanding of the sensitivity of the hydrological cycle to climate change is of great importance.

How these climate changes manifest themselves on a regional basis, the spacial and temporal redistribution of water resources and the environmental consequences are the main questions of practical importance for which answers are currently being sought.

It is the policy of the National Rivers Authorities in England and Wales to control river quality through the achievement of river quality objectives. The Emission Standards for discharges which would achieve the river quality objectives are called the Long Term Consent Conditions and methods of calculating Long Term Consent Conditions have been devised which ensure correct match with the river quality objectives (Warn & Brew, 1980; Warn, 1982).

In order to make correct use of sampling to assess compliance, the quality required of discharges and rivers has been defined

statistically. The favoured statistic is the 95-percentile; the concentration which can be exceeded only 5 percent of the time. This type of target concentration is called a 95-Percentile Limit. The requirement to achieve a particular concentration is called a performance target.

In recent years the world-wide tendency to degradation of the environment, due to man's activities, has provided an increased motivation for the analysis and control of the state of the environment. In particular, water quality modelling and management have become the subjects of systematic investigation.

The objectives of this study are to assess the likely effects of climate change on the quality of water in the River Thames. By using a water quality model, (QUASAR), on the lower reaches of the Thames and applying climate change scenarios, the changes in the distribution of water quality parameters can be assessed.

CHAPTER TWO

LITERATURE REVIEW

2.1. THE GREENHOUSE EFFECT AND CLIMATE CHANGE.

The greenhouse effect is a natural phenomenon that plays a central role in determining the Earth's climate and is, to a great extent, responsible for making the Earth conducive to life. In it's absence the Earth would be approximately 30 degrees colder. The physical mechanisms by which greenhouse gases warm the atmosphere are relatively well established and have been widely publicised in both scientific and non-scientific press (e.g. MacDonald, 1989; Luther & Ellingson, 1985; Doornkamp, 1989; Henderson-Sellers & Blong, 1989; Rowntree, 1990).

Terrestrial radiation emitted from the Earth's surface is partly absorbed by greenhouse gases, principally water vapour, carbon dioxide, methane, CFCs and nitrogen dioxide. With the exception of water vapour, all these gases have been increasing in concentration as a result of man's activities and their absorption maxima are in the 8-16 μm range of the spectrum where absorption by water vapour is weak (Figure 2.1). The longwave radiation re-emitted by the gases (at the temperature of the air at their level) is partly radiated back to the Earth where it warms the land, water and air masses

(Figure 2.2).

There is ample evidence that the atmospheric concentration of CO_2 has been rising steadily over past decades (Figure 2.3). The combustion of fossil fuels has been implicated as a primary cause of this increase (Figure 2.4. Jager, 1973; Lashof & Tirpack, 1991); a fact reflected in the global distribution of atmospheric CO_2 being greatest over the less vegetated and more industrialized Northern latitudes (Figure 2.5). As world population increases so too does the demand for energy (Figures 2.6 and 2.7) which, often being associated with increased standards of living, means that developing countries may well increase their relative contribution of CO_2 to the greenhouse effect (over that in the past; Figure 2.8).

Tropical deforestation accounts for approximately 10-35% of the annual anthropogenic CO_2 emissions (Figure 2.9), and 5-35% of the total anthropogenic N_2O emissions are attributed to nitrogen fertilizer consumption (Figure 2.10). Clearly, uncertainties arise as to the future levels of greenhouse gases emitted, when the underlying social, political and economic factors that govern production are far from predictable and clear-cut.

The consequences of increasing atmospheric concentrations of radiation absorptive gases are controversial (Arnell *et al.*, 1990). Uncertainties exist as to the rate at which gases are being emitted; which is dependent on the levels of economic

activity. The rate at which the CO_2 can be absorbed by plants and the oceans is far from certain (Volk, 1989), and, hence the importance of understanding the processes behind the ocean carbon cycle and its interactions on a global scale (Figure 2.11) has been highlighted by many authors (e.g. Mix, 1989; Harvey, 1989).

Reactions between important trace gases, their effects on sources and sinks of radiation absorptive gases, the feedback processes (Figure 2.12) and the implications for warming are all areas of uncertainty (Heymsfield & Miloshevich, 1991; Wigley, 1989; Covey, 1991). There is, however, agreement within the scientific community that increasing concentration of greenhouse gases will have far-reaching environmental and socioeconomic implications through the changes in climate it induces (Askew, 1987).

The Intergovernmental Panel on Climate Change (IPCC) Working Group II, responsible for assessing the impacts of such changes, has implicated the following global modifications (WMO, 1990):

i) an effective doubling of CO_2 in the atmosphere between now and 2025 to 2050 for a "business-as-usual" scenario;

ii) a consequent increase of global mean temperature in the range of 1.5°C to 4°-5°C;

iii) an unequal global distribution of this temperature increase, namely a smaller increase

of half the global mean in the tropical regions and a larger increase of twice the global mean in the polar regions; and

iv) a sea-level rise of about 0.3-0.5m by 2050 and about 1m by 2100, together with a rise in temperature of the surface ocean layer of between 0.2° and 0.25°C.

2.2. CLIMATE CHANGE AND THE HYDROLOGICAL CYCLE.

The Earth's climate is a result of the interplay of a vast variety of mechanical, physical, chemical and even biological processes which occur in our environment. Even if we understand the physical component of that complex interactive system, we have to contend with the behaviour of the:

- global atmosphere
- world oceans
- land surface hydrology
- sea-ice and polar ice-caps

Despite recent advances in climatology, climate forecasting is still a very complex and difficult task. Predictions of the climate and its effects on a global scale are now feasible by the utilization of general circulation models (GCMs). These are detailed, time-dependent, three dimensional numerical simulations that include atmospheric motions, heat exchanges and important land-ocean-ice interactions.

Hartmann (1990) briefly described the elements of current climate models and the physical processes incorporated in them. The structure of a typical GCM, designed for climate simulation during the 1970s and 1980s, is shown in Figure 2.13. A GCM uses the equations of motion to predict the temporal evolution of wind fields, which transport heat and moisture in the atmosphere. Models of vertical transport of heat by radiation and small-scale convection are included. The

latter is a highly simplified parametric model because the motions in these small-scale systems cannot be explicitly calculated in a global model with current computer technology. A GCM must also predict temperature, moisture content and snow cover for land surfaces.

However, the resolution of GCMs is not such that they are capable of providing necessary information on regional hydrological effects, and Gleick (1989) has argued in favour of water balance modelling as a method for obtaining more detailed estimates. In addition to the problem of coarse resolution, different GCMs present discrepancies on forecasting the regional distribution of the changes in climatic variables that determine regional hydrology (Dooge, 1989).

There is however, a certain degree of agreement between different GCMs regarding zonal estimates of the key hydrological parameters, temperature and precipitation. By constructing hypothetical scenarios of temperature and precipitation changes, based on the most recent and plausible scientific foresight, the sensitivity that watersheds exhibit in response to climatic perturbations may be investigated.

Increasing concentrations of greenhouse gases would have both direct and indirect effects on the hydrological cycle; initiating feedback mechanisms which in turn would influence climate at local and regional scales. It is clear to say that

changes in water resource availability consequent upon climatic change may be very significant, particularly if coupled with the changes in demand for water. Figure 2.14 summarises the key inter-relationships between climate change and water supply, demand and resource availability.

The most obvious effects of climate change would be on the magnitude, intensity, duration, frequency and timing of rainfall events. These changes cannot be predicted well on a regional scale. Increased heat will lead to greater evapotranspiration but the increase is expected to be partly offset by reduced plant water use in a CO_2-enriched atmosphere. Higher temperatures will have an impact on transitional snow zones, and greater precipitation will fall as rain instead of snow, therefore, increasing winter runoff and decreasing spring and summer snow melt volumes. If additional winter run-off can not be stored, then this may result in the loss of valuable water resources. In addition, higher temperatures will increase biological and chemical reaction rates, which will have further implications on the hydrological cycle.

Manabe and Wetherald (1986) used an atmospheric GCM coupled with a static mixed-layer ocean model to investigate the change in soil wetness in response to an increase (doubling) in atmospheric CO_2. Responding to an increase in CO_2, soil moisture in the model would be reduced in summer over extensive regions of the middle and high latitudes, such as the North American Great Plains, Western Europe, Northern

Canada and Siberia. According to the comparison of the surface water budget between the normal and high CO_2 experiments, the CO_2-induced reduction in soil moisture in summer over Siberia and Northern Canada results from the earlier disappearance of snow cover in the warmer climate. Since the snow cover has a high surface albedo, its disappearance increases the surface adsorption of solar energy and accordingly the rate of potential evapotranspiration. Thus the earlier termination of the snow-melt season results in the earlier commencement of the spring-to-summer reduction in soil moisture, causing the CO_2-induced reduction in soil moisture in summer.

Thornthwaite's water balance method and combinations of temperature and precipitation changes representing climate change were used by McCabe and Ayers (1989) to estimate changes in seasonal soil-moisture and runoff in the Delaware River basin. They found that winter warming could cause a greater proportion of precipitation in the northern part of the basin to fall as rain, which may increase winter runoff and decreases spring and summer runoff. In this humid temperate climate, where precipitation is evenly distributed throughout the year, decreases in snow accumulation in the northern part of the basin and increases in evapotranspiration throughout the basin could change the timing of runoff and significantly reduce total annual water availability unless precipitation were to increase concurrently.

Chunzhen and Yuying (1990), investigation the impact of

climatic change on the water resources for basins located in three climatic regions. Their results showed that runoff is highly sensitive to climatic changes in humid areas, and is weakly sensitive in nearly tropical areas. The variability of sensitivity depended mainly on the combination on increases (or decrease) of precipitation with decrease (or increase) of potential evapotranspiration in the various climatic regions.

Idso and Brazel (1984) point out the short comings of a study carried out by the US National Research Council. The NRC analysis suggested that watersheds in the western US will suffer 40-75% reductions in stream flow for a doubling of the atmospheric CO_2 content, leading to a 2°C rise in air temperature and a 10% drop in precipitation. However, this study made no attempt to include the direct antitranspirant effect of atmospheric CO_2 enrichment that would accompany any CO_2-induced climate change, whereby increasing CO_2 content of the air tends to induce partial stomatal closure, so reducing plant transpiration and thereby conserving soil moisture and increasing run-off to streams.

Idso and Brazel used an identical model employed by the NRC, to ensure valid comparability, then superimposed the antitranspirant effect on those results. When applied to 12 drainage basins in Arizona, their results indicated that 40-60% increases in stream flow may well be the more likely consequences of a CO_2 concentration doubling, even in the face of adverse changes in temperature and precipitation.

Aston (1984) simulated the effects of changed stomatal resistance likely under increased CO_2 content of the atmosphere on streamflow of an experimental catchment and a large water supply area. The results indicated that stream flow would be likely to increase from 40 to 90% as a consequence of doubling of atmospheric CO_2 concentration. Generally it was found that photosynthesis, growth and yield of C_3 plant species increased with higher ambient CO_2 levels, while the C_4 plants increases were insignificant.

Palutikof (1987) employed two methods to derive scenarios of runoff changes due to increasing concentrations of the greenhouse gases in ten drainage basins in England and Wales. The first method compared reconstructed riverflow data for the warmest and coldest twenty-year periods this century. This suggested riverflow would decrease in southern England and Wales and increase in northern areas. The second method attempted to introduce the direct effects of CO_2 on plant respiration into the analysis. In this scenario riverflow was expected to increase throughout the country.

Bultot *et al.* (1988; 1989) describe the likely modifications of meteorological variables in Belgium under the 2 x CO_2 climate conditions. They ran the daily-step conceptual hydrological model developed at the Royal Meteorological Institute of Belgium using data from typical Belgian catchments having sharply distinct characteristics: the Dyle catchment which has a thick aquifer in a sandy-loam soil; the

rock-bottomed Semois catchment; and the Zwalm river basin with sandy-clayey soils. The IRBM model was designed for the simulation of:

i) the water transfers:- interception of precipitation by vegetation, infiltration, evapotranspiration, surface run-off, deep percolation etc.;

ii) the status of the various phases of the water cycle:- water equivalent of the snow cover, water deposited on the vegetation canopy and on the ground surface, water content of the aeration zone of the soil as well as the zone of saturation etc. and;

iii) the flows at the outlet:- surface flow, baseflow, interflow, alluvial-zone flow.

To highlight the intricacies of such a simulation, a flow chart of the IRBM model is shown in Figure 2.15. Input climatological data are precipitation and potential evapotranspiration (PE), this latter element is computed by the energy balance method. Catchment particulars were taken into account: areas covered by various types of vegetation, albedos, leaf area indices (LAI), soil types (with a view to assessing the water retention capacity of the zone of aeration), and urbanization. These were assumed to remain constant throughout the course of time.

From November through March, the total flow augments

considerably in the three drainage basins. For the Semois and the Zwalm, the sole cause of this increase was attributed to the increases in surface flow. For the Dyle, the baseflow also contributed to the strengthening of the total flow, especially from January through March, as the precipitation influences to a larger extent the recharge of the aquifer in the Dyle basin. Due to its thick aquifer the strengthening of the baseflow is maintained all year round, so that the total flow is strengthened during summer also, and the risk of river pollution is thus lessened. In the Semois basin, between April and October, the total flow was found to decrease considerably as a result of a diminution of the surface flow (diminution of precipitation), of the interflow and of the baseflow (augmentation of the evapotranspiration). Hence, the Semois region could be exposed to a considerable increase of the pollution risk in the July and August period of low river stages.

Using a conceptual model of the water balance type, Mimikou *et al.* (1991) assessed the regional hydrological effects of climate change in a mountainous region of Greece, comprising three drainage basins: the Mesohora and Sykia basins of the Upper Acheloos River and the Pyli basin of the Portaikos River in west Thessaly. From their results, they concluded that mountainous, snow-covered Mediterranean basins with effective water-retentive characteristics under temperature increases exhibit reductions of soil moisture in general and more severely in summer, serious reductions of mean annual runoff,

even more serious reduction of mean summer runoff and increases of mean winter runoff accompanied by a shift of spring run-off. In warmer, humid basins or in general in basins where regional characteristics limit water retention, a minimal sensitivity of runoff to temperature change is exhibited.

Basin aridity appeared to be positively associated with the sensitivity of runoff to precipitation changes, and runoff, on an annual basis, seemed to be independent of temperature whereas on a seasonal basis it depended on the snow cover and hence on the temperature. Their results implicated snow (accumulation and melting) as the most significant and determining factor of basin response to climate change. This factor in turn depends on the orographic characteristics of the basin (altitude, area-elevation relationship, orientation) besides the general climatic ones. Additional characteristics were shown to be important, such as the coefficient of runoff which, when unusually high, does not permit other hydrological processes, sensitive to climate change, to be completed or even to take place at all.

2.3. RIVER WATER QUALITY.

The current trend in water management is towards multipurpose water use, and new legislation means that the "in-stream" quality is becoming as important as the "on-tap" quality.

Water pollution control activities are directed principally to protecting aquatic life and preventing undesirable conditions in streams that could arise as a result of low dissolved oxygen (DO) concentrations. To that end, most regulatory programs are heavily orientated toward controlling oxygen-demanding materials (BOD) in wastewater discharges. Therefore, the rationale behind planning, designing, operating, and monitoring wastewater treatment facilities is based largely on understanding the DO balance in water courses and maintaining desirable DO concentrations.

Classification systems for river quality has been proposed (e.g. Table 2.1) which restrict the use of a river's water with regard to its quality. Here, quality criteria are devised in terms of percentage saturation of dissolved oxygen, biological oxygen demand, pH, concentration of nitrates, ammonium nitrogen and unionized ammonia in the water. This means that consent discharges are often formulated with respect to the potential effects of these discharges on the fore mentioned quality parameters.

The oxygen balance in a watercourse is a result of combined

deoxygenation and reoxygenation reactions. Deoxygenation refers to the utilization of oxygen by various chemical and biological reactions, excluding the consideration of any reoxygenation that might occur simultaneously. The reactions may include immediate oxygen demand (caused by relatively rapid reactions between certain types of chemicals, for example sulphites, and DO in water), carbonaceous or biological oxygen demand (BOD), nitrogenous oxygen demand (NOD) and conceivably others as well.

Table 2.1. River Quality Standards.

	Class				
	1A	1B	2A	2B	3
DO (min)	80%	60%	40%	40%	10%
BOD (max)	3	5	9	9	17
Amm. N (max)	0.4	0.9	3.0	-	-
Unionized (max) ammonia as NH_3	0.025	0.025	0.025	-	-
pH	a	a	a	b	b
Nitrate	0.2	0.2	0.5	-	-

(a) range 6.0-9.0; (b) range 5.0-9.5
N.B. Figures are expressed (in general terms) as a 95%ile.

Figure 2.16 shows the major sources and sinks of carbonaceous BOD (CBOD) in natural waters. Anthropogenic inputs include point sources and non-point sources such as urban runoff and feedlot runoff. Autochthonous sources derived from the aquatic biota (particularly algae) can be important in some systems. Also, entrainment of oxygen-demanding material from benthic deposits may occur. Removal of CBOD from the water column occurs through sedimentation, microbial degradation and the sorption onto or uptake by the benthic flora. Some components of BOD may also volatilize from the water column. Carbonaceous material which has settled or been sorbed becomes part of the benthic oxygen demand, and from their study of the River Lark, Owens and Edwards (1963) stressed the importance of this demand in determining the overall oxygen distribution within shallow rivers in particular.

A number of factors such as water temperature, flow hydraulics, stream geometry and the nature of the carbonaceous material are known to influence the rate at which CBOD is removed from the water column. Like all biochemical processes, the CBOD decay rate increases with increasing temperature to a point where protein denaturation begins. Water turbulence is recognised as influencing the rate of BOD depletion in a receiving water in a number of ways. It influences the CBOD settling rate by controlling such processes as scour and sedimentation, and may enhance contact between the substrate and the benthic biological community.

Biological self-purification is the process by which organic wastes are broken down by the respiration of micro-organisms into stable end products. It is a biochemical oxidation process through which organic wastes are consumed leaving behind end products such as carbon dioxide, phosphates and nitrates. The water is 'purified' in the sense that the concentration of waste material has been reduced. Organic materials which can be broken down (i.e. are biodegradable) include natural materials such as simple sugars, starch, fats, proteins as well as more complex natural or synthetic compounds which are found in sewage or other wastes.

The interaction between BOD and DO downstream of a discharge may be illustrated in a simple manner as shown in Figure 2.17. A high initial BOD exerts a large demand for oxygen and as the in-stream organic matter decays the oxygen level becomes depressed. The river, however, has the capacity to recover naturally from this situation by reaeration at the atmosphere-water interface. This reaeration process (oxygen transfer) is primarily controlled by the degree of oxygen saturation, but is also enhanced by lower atmospheric temperatures and turbulence.

At the minimum point of the oxygen sag curve a high level of reaeration occurs and as the BOD level declines the DO level increases. The minimum is influenced by various factors including the type of effluent and the rate of discharge, a higher organic load producing a lower minimum. In addition, at

high river flows the location of the minimum shifts downstream.

Typically, the net transfer of oxygen is from the atmosphere and into the water, however, in circumstances when photosynthesis produces supersaturated DO levels, this net transfer is reversed.

Figure 2.18 illustrates nitrogen transformations in river systems. The transformation of reduced forms of nitrogen to more oxidised forms (nitrification) consumes oxygen. This is a two-stage process, the first being the oxidation of ammonia to nitrite by *Nitrosomonas* bacteria:

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+$$

Stoichometrically 48/14 or 3.43 gm of oxygen are consumed for every gram of ammonia-nitrogen oxidised to nitrite-nitrogen. During the second stage of nitrification *Nitrobactor* bacteria oxidise nitrite to nitrate:

$$NO_2^- + 0.5O_2 \rightarrow NO_3^-$$

Stoichiometrically 16/14 or 1.14 gm of oxygen are consumed per gram of nitrite-nitrogen oxidised. If the two reactions are combined, the complete oxidation of ammonia can be represented by:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$$

As expected, 64/14 or 4.57 gm of oxygen are required for the complete oxidation of one gram of ammonia.

In the reactions above, the organic-nitrogen form does not

appear since organic-nitrogen is hydrolysed to ammonia, and does not consume oxygen in the process. However, organic nitrogen will eventually contribute to the NBOD, as the following equation shows:

$$NBOD = 4.57\ (N_0 + N_1) + 1.14\ N_2$$

where:

N_0 = organic-nitrogen concentration,

N_1 = ammonia-nitrogen concentration,

N_2 = nitrite-nitrogen concentration.

The stoichiometric coefficients of 3.43, 1.14, and 4.57 in the previous equations are actually somewhat higher than the total oxygen requirements because of cell synthesis.

Modellers typically consider only temperature effects on nitrification, although a few do model DO limitations. However, additional factors including pH, ammonia and nitrite concentrations, suspended solids, and organic and inorganic compounds effect the rate of nitrification.

Oxygen demand by benthic sediments and organisms can represent a large fraction of oxygen consumption in surface waters. Benthal deposits at any given location in an aquatic system are the result of the transportation and deposition of organic material. The material may be from a source outside the system such as leaf litter or wastewater particulate BOD (allochthonous material), or it may be generated from inside the system as occurs with plant growth (autochthonous

material). In either case, such organic matter can exert a high oxygen demand under some circumstances. In addition to oxygen demand caused by decay of organic matter, resident invertebrates can generate significant oxygen demand through respiration.

It is generally agreed that the organic matter oxygen demand is influenced by two different phenomena. The first is the rate at which oxygen diffuses into the bottom sediments and is then consumed. The second is essentially the rate at which reduced organic substances are conveyed into the water column, and are then oxidised. Traditional measurement techniques do not differentiate between the two processes but measure, either directly or indirectly, the gross oxygen uptake. Hence, in modelling DO, a single term in the DO mass balance formulation is usually used for both processes. The process is usually referred to as the sediment oxygen demand (SOD).

The major factors affecting SOD are: temperature, oxygen concentration at the sediment-water interface (available oxygen), makeup of the biological community, organic and physical characteristics of the sediment, current velocity over the sediments, and chemistry of the interstitial water. Each of these factors is a resultant of other interacting processes occurring elsewhere in the aquatic system. For example, temperature and available oxygen can be changed as a result of transport and biochemical processes in the water column or system boundaries. Another important linkage is that

the biological community will change with the water quality (e.g. oxygen and nutrient concentrations) and productivity of the system. The organic characteristics will change over the long term due to settling of organic matter (detritus, faecal matter, phytoplankton) and its subsequent degradation and/or burial by continued sedimentation. The biological community and the organic and physical characteristics of the bottom sediments are usually treated as a composite characteristic of the particular system.

Photosynthetic oxygen production (P) and respiration (R) can be important sources and sinks of DO in natural waters. Many models simulate these processes directly on terms of algal growth and respiration. However, some water quality models use the approach that P and R can be modelled without the necessity of simulating algal activity. This approach is valid where P=0 and R=0, or else some type of curve, such as a sine curve or more generally a Fourier series, is used instead, where certain parameters must be delineated to characterise the curve. Other models simulate only daily averaged values. If, on a daily average basis, P-R is practically zero, these models would predict little effect of algal activity on DO. However, if P and R are both large numbers, then actual DO levels will be higher during the day and lower at night than predicted by the models.

In a collaborative study with Thames Water Authority, Whitehead and Hornberger (1984) developed algal models for the

River Thames. They examined the non-linear processes controlling algal growth using a generalized sensitivity analysis technique (Monte-Carlo simulations). The dominant parameters controlling system behaviour were identified as the growth rate, a power term included to enhance the self-shading factor at high algal concentrations, and the optimal solar radiation level which accounts for the decrease in algal growth under low light intensity and the apparent decrease in growth under extremely high intensity conditions in the Thames.

2.4. RIVER QUALITY MODELLING.

Streeter and Phelp's (1925) basic dissolved oxygen reaeration equation facilitated the use of mathematical models in the management of water quality in river basins. With increasing public awareness, pollution control legislation and improved computing techniques, the accuracy of these models has been improved. River quality models (RQMs) have now become important tools for managers and planners; to aid the management and control of river water quality and effluent discharges.

The application of mathematical models to water quality and pollution transport has been reviewed by many authors (e.g. Whitehead, 1984; Beck, 1985; BHRA, 1986). Crabtree *et al.* (1987) have briefly distinguished between types of RQMs in terms of their application (use:- research or management) and the representation of relationships and processes modelled (stochastic/deterministic, dynamic/steady-state, mechanistic/black box). There are three components within a river system which can be modelled to varying degrees of complexity:

i) the number and type of water quality parameters simulated;

ii) the temporal variability of the inputs and forcing functions (e.g. discharge quality and quantity);

iii) the simulation of the flow regime in the river system.

Hines *et al.* (1975) have diagrammatically illustrated the increasing complexity in the various biochemical interactions that can be modelled (Figure 2.19). This ranges from the simple mass balance representation for conservative minerals, through simple DO models to modelling complex eutrophic processes. The data requirements will increase as the complexity of the model's representation of the system increases.

The stages involved in the selection and use of RQMs are shown systematically in Figure 2.20. Clearly, the nature of the modelling problem will determine the type of model required, hance the design and thus capabilities of the models developed are often specific to these requirements.

To simulate the distribution of water quality in a river system throughout the year, with any accuracy, will require a RQM with a relatively complex representation of the river system. This should include the ability to model:

i) the effect of cyclic variations (e.g. seasonal and diurnal) in input parameters and system parameters;

ii) the correlation between inputs, so that realistic flow and quality mixing is maintained;

iii) the various potential consent limiting water quality constituents, and the significant factors affecting their concentration; and

iv) the complexity of river basins as physical and ecological systems.

In the UK there has been a tendency for the development of RQMs to suit specific problems. This has been due to the fragmentation of the agencies carrying out modelling exercises. In the USA the Environmental Protection Agency exerts a controlling influence on the development of water quality models. It has models and documentation for a wide range of applications, all of which are freely available. As a result there is a larger reservoir of knowledge and published data for each model.

Although there are differences in the modelling requirements in the UK, the lack of central development has produced duplication in modelling effort. This has led to little continuity of further application of models beyond their immediate implementation in a particular catchment and to a particular problem.(Crabtree *et al.*, 1985).

Thames Water Authority have produced a long-term consent setting model for catchment systems. The major constituent interactions in 'TOMCAT' are shown in Figure 2.21. This multi-shot model produces a series of independent quality simulations of the river system. During each 'shot' the various input values are randomly generated in such a way as to include the underlying cyclic variations found in the observed data.

The parameters modelled are DO, carbonaceous BOD, ammoniacal nitrogen and unionized ammonia. The DO balance is influenced

by reaeration, nitrification and BOD. Unionized ammonia is calculated from the concentration of ammoniacal nitrogen, the simulated pH and temperature. A plug-flow in the river is assumed, which does not take into account longitudinal dispersion. As it simulates high as well as low flow conditions this is a major simplification. The time of travel along any reach of the system is calculated using channel hydraulic characteristics and flow.

Any number of tributaries can be simulated, as well as effluent discharges, bifurcations, abstractions, weirs and river sampling points. As analytical solutions are used for the rate equations, there is no problem with numerical errors. However, there are system simplifications which could cause significant errors. These include plug-flow, the assumption that the underlying distribution of the residual errors do not vary with time, and the simplicity of the constituent interactions.

The USEPA general purpose model QUAL-II, has been successfully applied to the Blackwater catchment, a tributary of the River Thames, to examine the effects of various quality management options (Crabtree et al., 1985; 1986). This model has produced better predictive results than simpler UK developed deterministic models. However, in its standard form it has no stochastic components and cannot be used for consent setting. Its process representation is more sophisticated than 'TOMCAT', but its input requirements are similar. Ongoing

development with QUAL-II at Birmingham has produced a multishot stochastic-deterministic, one-dimensional, steady-state river model (SQUAL-1D) based upon the deterministic processes represented in QUAL-II. In effect QUAL-II forms the deterministic model which has stochastic input and output generated by Monte-Carlo simulation techniques. This approach was developed from the conceptual representation of temporal variability and mixing used by the 'TOMCAT' model.

A catchment simulation model (SIMCAT) has been used by Anglian Water for planning investment for river quality (Warn, 1987). Output from the model takes the form of a profile of water quality down the river. This shows the lengths of river where quality requires improvement. SIMCAT also employs the well established Monte-Carlo technique to calculate water quality standards for effluents by accounting for the variability of the polluting load and the variability of the dilution provided by the river. The effluent standards needed to bring all stretches of the river up to the required degree of compliance with the river quality targets can then be calculated, along with the costs of achieving these standards.

James and Elliott (undated) describe a dynamic water quality model (NUT) which is able to determine the frequency distributions of quality parameters such as DO and BOD with associated percentage compliance. These distributions can be determined over an annual period or shorter, for example during summer, when critical conditions are more likely to

occur. The duration or concentration relationships for each failure with compliance together with the time intervals between can also be calculated. This model has been applied to the Ely catchment to assist management in the evaluation of optimal consent conditions compatible with agreed river management strategies and objectives (Bird & Inverarity, 1988).

The NUT model has a modular structure. The main elements of the model may be briefly characterised as follows:

i) hydraulic inputs - data about flow, velocity, depth and cross-sectional area are read in at known sections for the times of observation. Intermediate values are obtained by interpolation in space and time. Coefficients of dispersion, reaeration and re-suspension are calculated from the hydraulic data;

ii) quality inputs - data on water quality at upstream boundary and initial conditions are read in together with loads. Loads and boundary conditions are specified at particular times and interpolated;

iii) coefficients for processes like BOD, SOD, photosynthesis etc. are read in at selected points and times and interpolated. Temperature corrections are applied;

iv) subroutines for handling all the main operations like interpolation, finite difference scheme, source and sink routines, output routines.

One main drawback of a model such as this is the additional data required for the calibration and validation procedures, however, this type of dynamic model approach does provide useful information for judging the consequences of alternative pollution control strategies.

There is, at present, considerable research into in-stream algae productivity and the consequences on water quality (e.g. Brinkman *et al.*, 1987). Auer and Effler (1990) have examined three methods for calculating daily average net photosynthetic oxygen production (net photosynthesis) in the water column with the goal of demonstrating the implications of method selection on the computation. Their results were intended to provide modellers guidance in selecting a particular approach. Their work would perhaps be a good starting point from which to build into QUASAR a more dynamic simulating of the function of algae.

The first method examined by Auer and Effler uses the photoperiod-average incident photosynthetically available radiation (PAR; 400-700nm) and Beer's law to compute irradiance at the middepth of the water column. That light value is applied to the P-I curve (which relates net photosynthesis and PAR; where I is the incident light) to determine the net photosynthetic rate corresponding to the photoperiod-average PAR at middepth. This rate is multiplied by the photoperiod (number of daylight hours/24) to yield the photoperiod-average rate of net photosynthesis. The dark-

period respiration is then subtracted to yield the daily average rate.

In the second method they employed, the incident light is attenuated over the water column to generate a vertical-light profile corresponding to the photoperiod-average PAR. Corresponding rates calculated from the P-I curve are then integrated over the water column to obtain the water-column average rate corresponding to the photoperiod-average PAR. This value is then corrected for the length of the photoperiod and dark-period respiration, to yield the daily average rate of net photosynthesis.

In method three, hourly integrated incident PAR is attenuated over the water column according to Beer's law to generate an hourly vertical PAR profile. Corresponding photosynthetic rates are calculated from the P-I curve and are vertically integrated to estimate the hourly average net photosynthetic rate. The daily average rate of net photosynthesis is calculated by integrating the houly water-column averages over the 24-hour period.

The use of the first and second methods introduces systematic errors because of the nonlinear character of the light attenuation and P-I functions. Method three avoids the systematis errors by calculating rates integrated over depth on an hourly basis and integrating over the day. Methods one and two overestimate the rate of the net photosynthesis at

average daily incident PAR values below about 100μEinsteins m_2 and overestimates rates above that level.

Whitehead *et al.* (1989) have reviewed models used in planning, design and operational management in the UK and Europe. They focused on the problems presented in relation to the control of agricultural nonpoint-source pollution. Among the likely future requirements that would be placed on existing models, they highlighted the need to improve techniques of parameter estimation, calibration and identification.

CHAPTER THREE

METHODOLOGY

3.1. THE THAMES STUDY SITE.

Figure 3.1 shows the Thames catchment area. The Thames study site from Cookham to Teddington is shown in Figure 3.2. The length of the main river is 236 kilometres with a fall of 108 metres. There are many locks and weirs along the course of the river. The weirs have a large effect on water quality since in addition to regulating depth, they largely control mixing and aeration in the reaches. Except in times of high flow the depth regulation results in low velocity of flow, long retention times, and a lower rate of aeration. The majority of the discharge within the Thames is from direct discharges, with little attributed to diffuse input along the course of the river. The river is navigable and is used by numerous small boats in the spring, summer and early autumn. This tends to increase the turbidity of the water as a result of scouring of bottom silts. The increased residence time associated with the resulting weirs is an important factor when considering water quality.

The quantities of sewage and trade effluent discharged to the Thames catchment above Teddington forms a high proportion of the total flow of the Thames at times of low flow. The location of principal sewage outfalls is an important consideration in defining the river reaches.

Whilst some water is abstracted for public water supplies from the River Thames above Oxford, from the River Kennet at Reading, and from a number of chalk and limestone springs the largest abstractions are made from the reaches of the Thames between Windsor and Hampton. The main abstractors are the Thames Water Authority, the North Surrey Water Company (NSWC) and Three Valleys Water Company, all of whom have intakes along these lower reaches. The principal reaches of concern in this study are shown diagrammatically in Figure 3.3 together with abstraction and discharge sites and tributaries. The length of the Thames modelled, from Cookham to Teddington has abstractions at:

- Staines
- Datchet
- Sunnymeads
- Egham
- Laleham
- Chertsey
- Walton (NSWC)
- Walton (TWA)
- Thames-Lee-Tunnel

and direct discharges from sewage treatment works at:

- Slough
- Windsor
- Chertsey
- Surbiton
- Hogsmill
- Esher

3.2. THE QUASAR MODEL.

QUASAR (Quality Simulation Along Rivers) is a water quality and flow model. The model has been designed at the Institute of Hydrology to assess the impacts of pollutants on river systems. The model was originally developed as part of the Bedford Ouse Study, a Department of Environment and Anglian Water Authority funded project initiated in 1972. The primary objective was to simulate the dynamic behaviour of flow and water quality along the river system (Whitehead *et al.*, 1979; 1981). Initial applications involved the use of the model within a real time forecasting scheme collating telemetered data and providing forecasts at key abstraction sites along the river (Whitehead *et al.*, 1984).

The model was also used within a stochastic or Monte-Carlo framework to provide information on the distribution of water quality within river systems, particularly in rivers subjected to major effluent discharges (Whitehead & Young, 1979). This technique was also used by Warn and Brew (1980) and Warn and Matthews (1984) to assess mass balance problems within river systems. There has also been a range of model applications to other UK rivers such as the Tawe in South Wales to assess heavy metal pollution, and the Thames to assess the movement and distribution of nitrates and algae along the river system (Whitehead & Williams, 1982; Whitehead & Hornberger, 1984).

A total of eight water quality variables can be simulated in

addition to flow, including nitrate, ionized and unionized ammonia, dissolved oxygen (DO), biochemical oxygen demand (BOD), pH, temperature, ortho-phosphate and any conservative pollutant or inert material in solution. To model these parameters the river is divided up into reaches. The reach boundaries are determined by points in the river where there is a change in the water quality or flow due to the confluence of a tributary, the location of a sewage treatment final effluent discharge, abstraction, or location of weirs. However, there is an underlying factor which promotes reaches of equal length for modelling purposes. Water quality changes due to biological or chemical reactions are also considered by ensuring appropriate reach lengths.

Two sets of equations have been developed to represent these nine parameters. One set consists of the differential equations relating to the rate of change of these parameters with time. These equations are solved by a "differential equation solver" subroutine in the program. The other set consists of "analytical solutions" or the integrated differential equations. These equations are solved at discrete time intervals, specified in the program as the model time step. The equations solved by QUASAR are given in Appendix A.

The model can be used in a planning mode or a dynamic mode. In the stochastic or planning mode a cumulative frequency curve and distribution histogram of a water quality parameter are generated. This provides information to aid in long term

planning of water quality management. In this mode statistical data of the water quality and flow in the first reach at the top of the river, and in tributaries, sewage treatment works discharges, and abstractions at key locations along the river are required. This data includes the mean, standard deviation, and shape of the probability distribution i.e. lognormal, rectangular, or gaussian. From these characterized distributions random numbers are generated as water quality and flow values. These values are then input into the model which essentially consists of a set of equations representing the water quality and flow. The values generated from the model equations represent the water quality and flow at the end of the reach. This output value is compared with the input value. If there is a difference of 1% or greater then the model is run again for that reach. (The same random number for the input value is used but the initial conditions generated from the current run is compared with the output value generated from the previous model run and are kept in the model equations.) This process is repeated either until steady state has been reached (i.e. the previously and currently generated value do not differ by greater than 1%) or up to 30 time periods. Five hundred and twelve random numbers and output are generated. The output is stored and used in producing cumulative frequency distributions and distribution histograms.

In the forecasting or dynamic mode the water quality and flow are simulated over selected periods. This allows the possible

affects of a pollution event on a river to be investigated. In this mode time series data is required for water quality parameters for the first reach of the river and for the tributaries, sewage treatment works discharges and abstractions along key locations on the river. The model run time step, i.e. the time interval over which the model will dynamically compute river quality and flow, and the run output length, i.e. the number of output steps that the model runs for, must also be specified. Once this data has been input the model can be run. A mass balance is performed at the beginning of each reach for inputs such as tributaries entering at that point on the river. The concentration change over the reach is solved using differential or analytical equations and the output from each reach is stored and used for the input of the next reach. The model is run for 20 time periods before the specified start of the model run using the "default" values to ensure that the system has reached equilibrium. The output values are used in generating profiles of water quality parameters along the river at a given time or in generating time series data at a specified location.

3.3. APPLICATION OF QUASAR TO THE THAMES.

There are two basic requirements before validation and calibration of the model to any catchment. First, water quality and flow data must be available for the river input at its top boundary and all subsequent key reaches. Secondly, the model must be able to accurately simulate the hydrograph at all locations using the daily data.

QUASAR models flow and water quality using data which it stores in the form of a map file. This data may be input to the map file by means of a program, written in Fortran 77, which will prompt the user for an output file name (i.e. the map file in which the data is to be stored), and the values to be input. The program then converts the data into the required format necessary for future use in running the model. Ideally, daily values for flow and water quality parameters are used as input to the model. This was the case for streamflow, but in some cases only data collected on a monthly basis was available, such as data for tributaries and discharges. In these circumstances the monthly average values may be interpolated and used on a daily basis. Data for the Thames River from Cookham to Teddington collected in 1974 was used to calibrate the model, and validation was carried out using data from 1975. These annual data sets, along with those collated for 1976 and 1989 were used in this study. The contrast in data, 1976 and 1989 being dry years, 1974 and 1975 being "normal" years, was an adequate test of the validity of the

model. A brief explanation of the structure of the map files is given in Appendix B.

Each map file thus contains all the data describing the river system to be modelled. Before running the model, a parameter set must be created from the map file which assembles all the input data into a format which can be easily edited by the user. A menu-driven display allows easy access to spatial data (reach length, width, depth, latitude and longitude) as well as flow volumes, water temperatures and rate coefficients (denitrification, BOD decay, nitrification, oxygen uptake by sediment, addition of BOD by dead algae, and photosynthetic oxygen production).

Once the map files and parameter sets are set up the model can be run. The user can specify the starting date and the time intervals of the run within the parameter sets, as well as the mode of running (i.e. planning or dynamic). After the model has been run, output data from any of the modelled reaches:

- Cookham to Boulter
- Boulter to Barge
- Barge to Down
- Down to Boveney
- Boveney to Datchet
- Datchet to Sunnymeads
- Sunnymeads to Egham
- Egham to Walton
- Walton to Teddington

are available for plotting. Further information on running the QUASAR model can be obtained from Black and McDougall (1989).

A range of climate change scenarios envisaged for the year 2050 were applied to the four years of data to assess the impacts on water quality and stream flow. Arnell (1991) has quantitatively assessed the impacts of climate change on river flow regimes in the UK. He applied a simple water balance model with a number of feasible change scenarios to 15 case study catchments. The model he used has three parameters notionally representing:

i) the proportion of rainfall which runs off directly into rivers;

ii) the lag between the creation of effective rainfall and its passage out of the catchment, and

iii) the relationship between actual and potential evapotranspiration.

From Arnell's work there are basically four (at least partially) independent variables:

i) summer change in rainfall (-16%, 0%, +16%)

ii) rest-of-year change in rainfall (0%, +8%, +16%)

iii) change in potential evapotranspiration (PE) in the summer (+7% and +15%)

iv) change in PE during the rest of the year (+7% and +15%)

These give rise to several (3x3x2x2=32) different scenarios. However, it is assumed that the wettest scenario for a given period of time corresponds to the lower increases in PE, and the driest scenario corresponds to the higher increase in PE.

The following eight tables illustrate these scenarios. N/A indicates where changes are not applied in view of the above assumptions. The numbers in each column are for winter, spring, summer and autumn respectively. The occasional additional number in brackets at the end of a column corresponds to the respective climate change scenario selected for application in this study.

Tables 3.1. Changes in Runoff.

Table 3.1a. Summer PE +7%, Rest of Year PE +7%.

SUMMER	AUTUMN, WINTER AND SPRING		
	0%	8%	16%
-16%	N/A	N/A	N/A
0%	N/A	7.5 5 3 5.5	36 26.5 3 39.5
+16%	N/A	7.5 5 25.5 5.5	36 26.5 25.5 39.5

Table 3.1b. Summer PE +15%, Rest of Year PE +7%.

SUMMER	AUTUMN, WINTER AND SPRING		
	0%	8%	16%
-16%	N/A	7.5 5 -27 5.5	36 26.5 -27 39.5
0%	N/A	7.5 5 -6 5.5	36 26.5 -6 39.5
+16%	N/A	N/A	N/A

Table 3.1c. Summer PE +7%, Rest of Year PE +15%.

SUMMER	AUTUMN, WINTER AND SPRING		
	0%	8%	16%
-16%	N/A	N/A	N/A
0%	-31.5 -26.5 3 -26.5	-4.5 -6 3 -5.5	N/A
+16%	-31.5 -26.5 25.5 -26.5	-4.5 -6 25.5 -5.5	N/A

Table 3.1d. Summer PE +15%, Rest of Year PE +15%.

SUMMER	AUTUMN, WINTER AND SPRING		
	0%	8%	16%
-16%	-31.5 -26.5 -27 -26.5 (4)	-4.5 -6 -27 -5.5	N/A
0%	-31.5 -26.5 -6 -26.5	-4.5 -6 -6 -5.5 (2)	N/A
+16%	N/A	N/A	N/A

Tables 3.2. Changes in Temperature.

Table 3.2a. Summer PE +7%, Rest of Year PE +7%.

SUMMER	AUTUMN, WINTER AND SPRING		
	0%	8%	16%
-16%	N/A	N/A	N/A
0%	N/A	2.9 2.0 2.0 2.0 (1)	2.3 1.2 2.0 1.2
+16%	N/A	2.9 2.0 1.2 2.0	2.3 1.2 1.2 1.2 (3)

Table 3.2b. Summer PE +15%, Rest of Year PE +7%.

SUMMER	AUTUMN, WINTER AND SPRING		
	0%	8%	16%
-16%	N/A	2.9 2.0 2.6 2.0	2.3 1.2 2.6 1.3
0%	N/A	2.9 2.0 2.0 2.0	2.3 1.2 2.0 1.2
+16%	N/A	N/A	N/A

Table 3.2c. Summer PE +7%, Rest of Year PE +15%.

SUMMER	AUTUMN, WINTER AND SPRING		
	0%	8%	16%
-16%	N/A	N/A	N/A
0%	3.5 2.6 2.0 2.6	2.9 2.0 2.0 2.0	N/A
+16%	3.5 2.6 2.0 2.6	2.9 2.0 2.0 2.0	N/A

Table 3.2d. Summer PE +15%, Rest of Year PE +15%.

SUMMER	AUTUMN, WINTER AND SPRING		
	0%	8%	16%
-16%	3.5 2.6 2.6 2.6 (4)	2.9 2.0 2.6 2.0	N/A
0%	3.5 2.6 2.0 2.6	2.9 2.0 2.0 2.0 (2)	N/A
+16%	N/A	N/A	N/A

It is from the previous tables that the four "best choice" scenarios used in this study were selected:

Scenario 1: "best" rainfall estimate: PE +7%

Scenario 2: "best" rainfall estimate: PE +15%

Scenario 3: "wettest" estimate: PE +7%

Scenario 4: "driest" estimate: PE +15%

A Fortran program was used to adjust the basic map files (herein after referred to as "original" data or map files) by applying the following changes to incorporate the potential effects on the hydrological cycle of a change in climate:

Table 3.3. Percentage change in runoff for selected climate change scenarios.

Scenario	Winter	Spring	Summer	Autumn
1	7.5	5	3	5.5
2	-4.5	-6	-6	-5.5
3	36	26.5	25.5	39.5
4	-31.5	-26.5	-27	-26.5

Table 3.4. Changes in temperature (celsius) for selected climate change scenarios.

Scenario	Winter	Spring	Summer	Autumn
1	2.9	2.0	2.0	2.0
2	2.9	2.0	2.0	2.0
3	2.3	1.2	1.2	1.2
4	3.5	2.6	2.6	2.6

The temperature is gained from an estimate of +2.2 degrees overall (including winter and subject to errors of +0.6 or -0.7) and winter increases of +2.3 to +3.5. The runoff was calculated from CCIRG (Climate Change Impact Review Group) rainfall scenarios.

CHAPTER FOUR

RESULTS AND DISCUSSION

Model output was generated for Datchet, Egham and Teddington (Figure 3.2). These sites were selected in view of their separation along the river system and, therefore, contrasting water quality. They are also sufficiently downstream of Cookham, the upper most site of the reach system and the location where input data was generated for the model. The results of the climate change scenario runs (1-4) are given in Tables 1 to 4 in Appendix C; these correspond to the results using data from years 1974, 1975, 1976 and 1989 respectively. These tables present the changes observed, from modelled original data (for the four years), under specified climate change scenarios. Firstly, comparisons of the original data are made between the years. With the inherent variability in year to year climate borne in mind, the impact of the climate change scenarios on water quality is assessed.

4.1. MODELLED ORIGINAL DATA.

4.1.1. Flow and Temperature.

Figure 4.1a compares the original annual flow regimes for the years 1974, 1975, 1976 and 1989 at Datchet. The general seasonal regime is clearly visible, with lower summer and higher winter discharges. The annual variation in flow is a reflection of the changes in precipitation, evapotranspiration and storage throughout the year. Increased biomass production

during warmer summer months promotes higher evapotranspiration rates, which, together with reduced precipitation, lead to lower river discharges. As precipitation increases in winter, soil moisture deficits will be reduced and will, along with reduced evapotranspiration (due to biomass decline and lower temperatures) yield higher flows. The annual variation in demand for water can also feature heavily in the flow regime of a river system, particularly once such as the Thames, with a highly populated catchment. Data for 1974 typifies this annual regime with peak discharges of greater than 250 cumecs in February, and about 300 cumecs in November. 1975 also has similar flows in February, but the summer minimum flows barely increase at the end of the year. 1976 was a particularly dry year with very low flows throughout most of the year and only returned to normal during September. Similar low flows were experienced in the summer of 1989 but, in contrast to 1976, spring and autumn discharges were approximately normal.

Similar annual variation is observed at Teddington (Figure 4.1b). Here, downstream of Datchet and Egham, the flow is somewhat higher as a direct result of the increased drainage area and limited water abstraction points. Table 4.1 compares the flow distributions at the three sites during each year. Along with Figures 4.1a and 4.1b, this table highlights the very low flows during 1976 and 1989, the 5-percentile flow distribution (Q95) being particularly low during 1976 at 5 cumecs at all three sites. (Clearly, Datchet and Egham are similar in flow regime, as indeed they are in most aspects,

i.e. water quality, see Tables 1 to 4 in Appendix C). Due to this lack of contrast results are only presented for Datchet and Teddington.

The original river water temperatures throughout the four years at Datchet and Teddington are shown in Figure 4.2a and 4.2b, respectively. At both sites the temperature was generally lower throughout 1974 than any other year. This difference is even more evident during the summer, where at both sites the temperature fails to rise above 20°C compared to peaks above 20°C during 1975 and approaching 25°C in 1976 and 1989. In addition, there is less variation in the daily temperatures in 1974 than during subsequent years. In particular, perturbations in the temperatures are observed during 1975 and 1976.

4.1.2. Dissolved Oxygen.

The original % saturation of dissolved oxygen during the four years for both sites are shown in Figures 4.3a and 4.3b for Datchet and Teddington, respectively. Table 4.2 shows the corresponding distributions at these sites. At both Datchet and Teddington all 4 years begin and end (i.e during January, February and December) with similar concentrations. Progressing through each year, the saturation rises to 150% at both Datchet and Teddington during all four years except at Datchet in 1974 and 1989, where maximum concentrations in both cases fall slightly short of this value. This rise in concentration is observed earliest in 1976 and additionally,

is steeper at Teddington than Datchet. A steeper rise in concentration is also observed during the remaining years (with the rise occurring in the order 1974, 1989 and lastly 1975). At this point it is worth noting that the plateaux observed when DO reaches 150% saturation are due to the nature of the model QUASAR which does not permit DO saturation to exceed this value (DO greater than 150% saturation would be unlikely to occur to occur in the Thames).

At Datchet these optimum % saturation of DO arising in April to May time remain until mid June, when dramatic decreases to zero occur during 1976 and 1989, and below 50% saturation during 1975. In 1974 however, the % saturation remains above 50% throughout the entire year. In addition, the minimums observed under the different years are displaced somewhat, with the minimum in 1976 occurring earliest in the year, followed by that for 1989 and 1975. After returning to its maximum value of 150% saturation at the beginning of August, the % saturation in 1976 declines again to a second minimum of just below 50% saturation. It recovers from this around mid September, where again, it reaches 150% saturation. After this, only the reduction in % saturation to its December value is observed. A similar pattern is observed during 1989 but there is only one minimum and the recovery of the % saturation of dissolved oxygen is slightly later than during 1976 (and does return to the prior % saturation value). In 1975, after the recovery from the minimum, which occurs later still than during 1989 (August as opposed to July), the maximum %

saturation is maintained into December.

At Teddington, the DO remains above 60% saturation for all four years (Figure 4.3b). Although depressions occur at this site, they are not as low as those observed at Datchet. The most dramatic difference between Datchet and Teddington is that during 1976 no exceptional minimum is observed during the summer months, but values decline from about the end of September, in two steps (the first in October,at about 120 % saturation, and the second in November), to eventually reach the December value of about 95 % saturation. In addition, the minimum concentration observed during 1989 has a steeper descent and is sooner than at Datchet, but recovery is also sooner and steeper than at Datchet. The same is true for the 1975 minimum, meaning that these low oxygen conditions are maintained over a shorter time than at Datchet. The other notable difference between the two sites is the second minimum observed at Teddington at the start of November 1989. No such phenomenon occurs at Datchet. This may be a consequence of the warmer temperatures at Teddington during October and November 1989 (Figure 4.2b), which may well have promoted algal growth late in the year with the resultant oxygen depletion. This reduced oxygen content is however, short-lived and constitutes no great threat to the river ecosystem as concentrations above 60% saturation are still maintained.

4.1.3. Biological Oxygen Demand.

In general, BOD (mg/l) increases during the summer months as

higher temperatures facilitate faster chemical and biological reactions. This was typical for all years at both Datchet and Teddington (Figures 4.4a and 4.4b respectively). At Datchet the BOD remains below 7 mg/l throughout each year except 1974, where a peak of almost 12 mg/l is observed in mid May. The maxima during the other years are observed in mid April in 1976, mid June in 1975, and the end of July in 1989.

At Teddington the BOD is higher, with the yearly maxima for 1974 at approximately 10 mg/l. During 1974 three periods are observed where the BOD rise is significant. The first of these corresponds to that found at Datchet, but is of a higher magnitude, approaching 10 mg/l. The second peak of 44 mg/l may be attributed to a series of sewage effluent inputs to the river at Hogsmill. Here, the BOD of effluent discharged upstream of Teddington was higher than 79 mg/l over the period from 11th to 16th June and peaked at a value of 249 mg/l on 13th June.

4.2. MODELLED CLIMATE CHANGE SCENARIOS.

Preliminary investigation of the results from the climate change scenario runs, both in terms of the changes in distributions of the water quality parameters and in terms of time series analysis, disclosed significant changes to occur under the scenarios for the DO concentrations and the BOD. No significant changes were observed in the concentrations of nitrates, ammonia or ortho-phosphate, and no water quality class boundary changed.

The effect of the climate change scenarios may be more pronounced in the results of the dissolved oxygen and biochemical oxygen demand than for the remaining parameters modelled because there are many processes within the model which are linked to DO and BOD, and are affected by the change in climate (i.e. will change with temperature in particular) and which then affect the DO and BOD. In contrast, fewer process in the model affect the concentrations of nitrates ammonia and ortho-phosphate, so these parameters remain more stable when the climate change scenarios are applied. In view of these results, presentation of the details of the impact of climate change on water quality are only discussed for DO and BOD.

4.2.1. Flow and Temperature.

The application of the climate change scenarios to the original flow and temperature data has very predictable

results. From Tables 3.3 and 4.4 it is clear how these changes will manifest themselves. The temperatures under the climate change scenarios will simply alter according to the seasonal adjustments given in Table 3.3. The absolute changes in flow, on the other hand, will be dependent on the original flow as adjustments are made in terms of percentage changes. Figures 4.5 and 4.6 have been included to highlight this point. Figure 4.5 shows the original temperature throughout 1974 at Datchet with the changes induced under scenarios 3 and 4, these being the most extreme changes of all the scenarios. Figure 4.5 shows the original flow throughout the same year, also at Datchet. Here the adjustments under the extreme scenarios are also shown, but unlike the temperature changes, the high original flows cause even higher (under the "wetter" conditions of scenario 3) or lower (under the "drier" conditions of scenario 4) resulting flows due to the percentage changes in Table 3.4. As a consequence, little absolute change is observed during the typical low summer flows, but greater change under the higher winter flows.

4.2.2. Nitrate, Ammonia and Ortho-phosphate.

The maximum change in nitrate concentration was observed in 1974 under scenario 4 where the 95-percentile value at Teddington increased by 18%, however, this constituted an absolute change of less than 1.5 mg/l. The maximum change in ammonia concentration was observed in 1976, also under scenario 4 where the 95-percentile value increased, again at Teddington, by 20%. Once more, this constituted an absolute

increase of only 0.14 mg/l. An absolute increase of 0.86 mg/l in the 95-percentile value for the ortho-phosphate concentration was observed in 1989 at Teddington under scenario 4, and was the greatest change in this parameter observed under the scenarios.

4.2.3. Dissolved Oxygen and Biochemical Oxygen Demand.

Tables 4.4 to 4.7 show the changes in the mean values of DO and BOD when the climate change scenarios were applied. These changes are expressed in both percentage terms and as absolute values, and were derived from Appendix C.

The mean concentrations of DO (mg/l) were found to at both Datchet and Egham. The relationship between DO concentration and flow volume and water temperature suggests that under the highest temperatures and evapotranspiration rates (i.e. climate change scenario 4) the greatest decrease in concentration could be expected. This is because the potential for reaeration from the air-water interface will be reduced when the stream is less turbulent under the lower flows. In addition, longer residence times will facilitate greater oxygen consumption, and increases in temperature will lower the solubility of oxygen. Conversely, the "wettest" conditions (i.e. scenario 3), with highest flow volumes and smallest temperature increases would be expected to present the smallest change in DO. This was generally found to be the case, as shown by the changes in mean values in Tables 4.4 to 4.7.

Tables 4.4 to 4.7 also show the changes in the mean DO in terms of percentage saturation observed under each scenario. During every year the original mean % saturation of DO increases from Datchet to Teddington, and the changes induced under the scenario runs decrease. Generally, the % saturation of DO decreases under every scenario, more so during the "drier" conditions of scenario 4, and to less of an extent under the "wettest" conditions of scenario 3. The intermediate climate change scenarios, 1 and 2, generally give rise to intermediate changes.

Tables 4.4 to 4.7 also show the changes in mean BOD (mg/l) observed under the climate change scenarios. The original mean BOD increases from Datchet to Teddington as the sewage effluent input from Datchet to Teddington increases, and it appears that only at Teddington was there any significant change in this value. Here, decreases in the mean occurred under scenario 3, and increases under scenario 4. This is perhaps not unexpected as during wetter years higher flows will allow greater dilution. There is however, a decrease in the residence time under increased flow conditions, which will mean there is essentially less time over which biological and chemical activity can reduce the BOD. There is thus conflict between the dilution effect and the BOD decay rate and further attention to the distribution of the BOD over time must be paid in order to clarify this situation. During drier and warmer years there is every possibility that increased BOD is a result of increased in-stream algal productivity leading to

growth and decay cycles which can have a profound effect on the BOD.

Of greater significance, as far as water quality objectives and setting consent discharges are concerned, is the distribution of water quality parameters throughout the year. In particular, the 95-percentile distributions for BOD (mg/l) and the 5-percentile distributions for DO (% saturation) are of great importance. Tables 4.8 to 4.19 show the changes in the 5-percentile and 95-percentile distributions observed under the climate change scenarios for the four years of data. It has been established that changes observed under scenarios 1 and 2 are generally intermediate in magnitude to those observed under the extreme scenarios, 3 and 4. This being the case, time series graphs have been produced, for the parameters of concern, which compare the original data for each year (as shown in Figures 4.1a and 4.1b to 4.4a and 4.4b) with the results obtained under the "wettest" and "driest" climate change scenarios, i.e. scenarios 3 and 4 respectively.

The changes to the original DO (% saturation) observed at Datchet under scenarios 3 and 4 for data from 1974, 1975, 1976 and 1989 are shown in Figures 4.7a to 4.10a respectively. During every year, the % saturation of DO begin at more or less the same values under both scenarios shown as under the original data. The increase in DO towards the summer months observed in the original data is replicated in both scenarios, however, under scenario 4 this increase occurs to a greater

extent than in the original. Under scenario 3 no real difference from the original is observed during this beginning-of-year increase. The first depression in the original data near the middle of the year is also replicated to some degree by both scenarios. Under the dry conditions of scenario 4, the decrease towards the minimum summer value begins slightly sooner than under the original climate, and also reaches a lower value, particularly in 1974, where the original DO does not fall so low (in 1974 the original minimum remains above 50% saturation, whereas in the other years this minimum approaches zero). The recovery observed towards the end of the summer occurs later under scenario 4; at about the beginning of September in 1974, but not until the end of September in the other years. At this point in time in 1975 (Figure 4.8a), the % saturation of DO increases above the original until the end of November. In 1976 (Figure 4.9a), where a second depression is observed in the original data, the depression is again lower under scenario 4, and in fact recovery of the DO between these two depressions is poor; under scenario 4 the DO saturation remains below 40% saturation, compared to a recovery up to 150% under the original data. At the end of the year the DO under both scenarios levels off at about the same value as the original (i.e. 100 % saturation).

Under the "wettest" conditions of scenario 3 a similar situation is observed as under scenario 4, except to less of an extent. Figures 4.7a to 4.10a clearly show the values under

scenario 3 to be generally between those of the original data and those of scenario 4.

The changes in % saturation of DO from the original concentrations observed under scenarios 3 and 4 at Teddington are shown in Figures 4.7b to 4.10b during 1974, 1975, 1976 and 1989 respectively. As with Datchet, the original summer increase in DO is reproduced under scenario 3 and observed earlier under scenario 4. However, this is only true for 1974 and 1975, and no change from the original is found under the other two years. The maximum concentrations during the summer months observed under the original climate are reproduced under both scenarios. During 1976 however, an additional decrease in concentration at the end of June to about 70% saturation is observed under scenario 4 which was not found under the original climate. This may be caused by the higher temperatures under scenarios 4 (and particularly during this drought year) increasing biomass production which then adds to the BOD. The decreases in summer concentration in the original data for 1975 and 1989 is reproduced under both scenarios, and like at Datchet, this decrease is shown sooner (and remains for a longer time) under scenario 3 (and more so under scenario 4). At Datchet in 1976, recovery from the first minimum before entering the second was less under both scenarios. At Teddington in 1975, recovery from the first minimum before the second, (Figure 4.8b) was greater under scenario 4 and less under scenario 3 (than the original). The remaining three years show the reduction in concentration

towards the December value to be later under scenario 4 and sooner under scenario 3 than under the original climate. Towards the end of every year an additional minimum in DO concentration is observed under scenario 4. The timing of this event varies from year to year; in 1974 at the beginning of September, 1975 at the end of September, 1976 at the end of October, and extending through November until nearly the end of the year in 1989. A reason for this may be the fact that as the years become generally warmer from 1974 to 1989 (Figure 4.2b), particularly from September to December, the algal growing season is extended and oxygen reduction as a result of their death and degradation occurs later on in the annual cycle.

These DO time series indicate the impact of enhanced water temperatures may have on the stream biota. Increased summer temperatures may cause prolific oxygen exhaustion during decay of algae which, under the aforementioned conditions have grown rapidly. It may be the case that the summer blooms cause concentrations of DO to plummet to almost zero, as was observed under scenario 4 in all years but 1976, and that as the algae growing season is extended through to the mild autumn the time over which this oxygen depletion occurs is also extended.

There may be cause for concern if this is the case as the distribution of DO through the year changes. Tables 4.9, 4.12, 4.15 and 4.18 show the changes in the 5-percentile values and

the 95-percentile values observed under all the climate change scenarios. On the whole, little change is observed in the 95-percentile values under the scenarios, but for DO (% saturation) it is the 5-percentile value that is of importance in determining the water quality objectives. The water quality classification system outlined in Table 2.1 specifies the minimum concentrations of DO (% saturation) over 95% of the time for five water quality classes. These concentrations correspond to the 5-percentile values in Tables 4.9, 4.12, 4.15 and 4.18, and clearly a great deal of change is observed under most scenarios.

The changes from the original BOD over the four years at Datchet observed under the extreme climate change scenarios are shown in Figures 4.11a to 4.14a. On the whole the climate change scenarios induce little change in any year. In all but 1975 the climate under scenario 4 causes the summer peak in BOD to be slightly reduced and to be slightly increased under scenario 3. This is reversed during 1975.

Figures 4.11b to 4.14b show the changes from the original BOD at Teddington observed under the extreme climate change scenarios over the four years. For all years the BOD observed under scenario 4 is generally higher than that originally observed. In 1974 this still holds true, but in the main summer peak, the maximum under scenario 4 is slightly lower than the original, but resumes a higher value than the original once the peak subsides. In both 1974 and 1975 an

additional peak in the BOD over and above that found in the original data is observed in September under scenario 4. The most dramatic change observed under scenario 4 is during 1989, where, as well as the original perturbations in the data being increased in magnitude, additional maxima in BOD are observed at the beginning and end of the year. These periods of high BOD, not surprisingly, correspond to the periods of low DO concentration observed in Figure 4.10b (from the intrinsic nature of the relationship between the two).

Generally little change is observed under scenario 4 in the 95-percentile distribution of BOD (Tables 4.10, 4.13, 4.16, and 4.19). The only notable changes were at Teddington in 1975, 1976 and 1989 where this distribution increases by 18, 25 and 21% respectively, which could have great impact on water quality objectives (Table 2.1).

In every year the BOD under scenario 3 was generally less than that observed in the original data. Under these wetter conditions the higher flow regime gives rise to a greater dilution effect. As may be expected, the 95-percentile distribution decrease slightly under scenario 3.

4.2.4. Implications Of Climate Change Impacts On Water Quality Classification.

Under the climate change scenarios applied in this study, no changes in the river quality class (Table 2.1) would be

expected in terms of BOD and the other modelled water quality variables. However, when consideration is taken of the DO (% saturation), and the changes in its distribution observed under the scenarios, important river quality class changes will occur. The most deleterious changes in river quality would occur under drier years such as 1976 and 1989. For example, during these years the water quality class at Teddington is reduced form class 1A to class 1B under scenario 4. Whereas no change in water quality class is observed here in 1974 under the same scenario, and the quality (as determined by the 5-percentile distribution) actually increases for 1975.

Table 4.20 summarizes the changes in the water quality class that would be likely under the extreme climate change scenarios. All three sites (Datchet, Egham and Teddington) are included in this table, and reference is only made to changes that would occur in regards to the % saturation of DO. The original water quality class is also specified with regards to the DO (and would, in reality, be determined from a number of other additional parameters).

Table 4.1 Distribution of original flow data.

FLOW DISTRIBUTION (cumecs)	ORIGINAL DATA YEAR			
	1974	1975	1976	1977
DATCHET				
Mean	62	55	23	45
Standard Deviation	53	56	33	44
5-percentile	14	13	5	15
95-percentile	172	184	96	150
EGHAM				
Mean	62	57	20	38
Standard Deviation	59	62	35	42
5-percentile	11	12	5	10
95-percentile	184	204	97	140
TEDDINGTON				
Mean	80	73	24	39
Standard Deviation	82	81	45	51
5-percentile	12	14	5	6
95-percentile	258	156	118	161

Table 4.2 Distribution of original dissolved oxygen (% saturation).

DISSOLVED OXYGEN DISTRIBUTION (% SATURATION)	ORIGINAL DATA YEAR			
	1974	1975	1976	1977
DATCHET				
Mean	91	95	99	95
Standard Deviation	16	30	44	29
5-percentile	71	42	3	18
95-percentile	123	150	150	132
EGHAM				
Mean	96	105	120	107
Standard Deviation	18	25	26	28
5-percentile	91	78	90	72
95-percentile	133	150	150	150
TEDDINGTON				
Mean	106	105	128	118
Standard Deviation	23	25	27	28
5-percentile	84	78	87	82
95-percentile	150	150	150	150

Table 4.3 Distribution of original biochemical oxygen demand.

BIOCHEMICAL OXYGEN DEMAND (mg/l) DISTRIBUTION	ORIGINAL DATA YEAR			
	1974	1975	1976	1977
DATCHET				
Mean	3.7	3.4	3.4	2.4
Standard Deviation	2.2	1.6	1.1	1.1
5-percentile	2.0	1.4	2.0	2.3
95-percentile	9.5	6.7	6.9	4.8
EGHAM				
Mean	3.7	3.5	3.8	2.6
Standard Deviation	2.0	1.3	1.3	1.1
5-percentile	2.2	1.8	1.9	1.3
95-percentile	9.0	6.0	7.1	4.6
TEDDINGTON				
Mean	4.3	4.2	5.8	3.2
Standard Deviation	1.7	1.7	2.8	1.2
5-percentile	2.8	2.4	2.8	1.9
95-percentile	8.6	7.3	9.2	5.2

Table 4.4. Changes in mean values from 1974 original data observed under climate change scenarios.

SITE	ORIGINAL MEAN	CLIMATE CHANGE SCENARIO							
		1		2		3		4	
		%	A	%	A	%	A	%	A
DO (mg/l)									
D	9.90	-8	.84	-9	.86	-4	.38	-14	1.37
E	10.53	-5	.56	-5	.50	-4	.39	-5	0.57
T	11.51	-3	.32	-2	.25	-3	.33	-2	0.27
DO (% SAT)									
D	91.07	-5	4.2	-5	4.45	-1	.79	-10	8.89
E	95.91	-1	.73	-	.15	-1	.57	-	.29
T	106.19	2	2.1	3	2.86	+	.18	4	4.32
BOD (mg/l)									
D	3.67	-1	.02	-2	.07	2	.07	5	.20
E	3.67	-1	.02	-1	.05	2	.05	4	.16
T	4.29	-1	.06	-1	.03	-2	.09	4	.18

N.B. % = Percentage change from mean of original 1974 data observed under climate change scenarios.
A = Change from mean of original data in absolute terms.
+ or - alone denotes possitive or negative values less than 0.5%.
D = Datchet E = Egham T = Teddington

Table 4.5. Changes in mean values from 1975 original data observed under climate change scenarios.

SITE	ORIGINAL MEAN	CLIMATE CHANGE SCENARIO							
		1		2		3		4	
		%	A	%	A	%	A	%	A
DO (mg/l)									
D	10.41	-11	1.2	-11	1.1	-8	.84	-13	1.3
E	11.44	-7	.79	-6	.67	-7	.77	-6	.69
T	12.57	-5	.66	-5	.63	-4	.50	-7	.89
DO (% SAT)									
D	95.24	-9	8.12	-8	7.9	-6	5.9	-10	9.2
E	105.28	-3	3.44	-2	2.2	-4	4.5	-1	1.2
T	105.28	9	9.45	9	9.8	9	9.3	8	8.9
BOD (mg/l)									
D	3.41	-1	.03	-2	.06	1	.04	-5	.16
E	3.45	-1	.04	-1	.04	-1	.05	-1	.05
T	4.22	-2	.10	+	.01	-7	.29	12	.51

N.B. % = Percentage change from mean of original 1975 data observed under climate change scenarios.
A = Change from mean of original data in absolute terms.
+ or - alone denotes possitive or negative values less than 0.5%.
D = Datchet E = Egham T = Teddington

Table 4.6. Changes in mean values from 1976 original data observed under climate change scenarios.

SITE	ORIGINAL MEAN	CLIMATE CHANGE SCENARIO							
		1		2		3		4	
		%	A	%	A	%	A	%	A
DO (mg/l)									
D	10.77	-12	1.34	-12	1.31	-9	.92	-16	1.69
E	12.72	-6	.77	-5	.64	-6	.74	-4	0.56
T	13.48	-3	.41	-3	.37	-2	.31	-7	0.93
DO (% SAT)									
D	99.46	-10	9.81	-10	9.55	-7	6.8	-12	12.4
E	120.78	-1	1.40	-	.47	-2	3.4	1	1.5
T	128.07	1	1.52	2	2.06	+	.47	-	.61
BOD (mg/l)									
D	3.39	-2	.06	-3	.10	2	.07	-7	.25
E	3.75	+	.01	-2	.06	-2	.06	0	0
T	5.79	-4	.24	1	.07	-11	.63	24	1.4

N.B. % = Percentage change from mean of original 1976 data observed under climate change scenarios.
A = Change from mean of original data in absolute terms.
+ or - alone denotes possitive or negative values less than 0.5%.
D = Datchet E = Egham T = Teddington

Table 4.7. Changes in mean values from 1989 original data observed under climate change scenarios.

SITE	ORIGINAL MEAN	CLIMATE CHANGE SCENARIO							
		1		2		3		4	
		%	A	%	A	%	A	%	A
DO (mg/l)									
D	10.08	-11	1.08	-11	1.07	-7	.66	-15	1.56
E	11.17	-8	.91	-7	.79	-7	.78	-8	0.88
T	12.13	-7	.88	-7	.87	-5	.63	-14	1.72
DO (% SAT)									
D	95.43	-7	7.14	-7	6.94	-4	4.0	-12	11.6
E	107.21	-5	4.90	-3	3.56	-5	5.0	-3	3.2
T	117.62	-4	4.72	-4	4.46	-3	3.6	-10	11.3
BOD (mg/l)									
D	2.39	-1	.03	-1	.03	-	.01	-2	.05
E	2.55	-2	.05	-1	.03	-3	.08	2	.05
T	3.22	-4	.12	+	.01	-9	.28	20	.64

N.B. % = Percentage change from mean of original 1989 data observed under climate change scenarios.
A = Change from mean of original data in absolute terms.
+ or - alone denotes possitive or negative values less than 0.5%.
D = Datchet E = Egham T = Teddington

Table 4.8. Percent change in 5 and 95 percentile distributions for dissolved oxygen concentration (mg/l) under selected climate change scenarios using data from 1974.

SITE	CLIMATE CHANGE SCENARIO							
	1		2		3		4	
	5%	95%	5%	95%	5%	95%	5%	95%
D	-32	0.2	-34	2.5	-4.4	-2.6	-60	5.2
E	-8.6	0.5	-8.4	3.2	-2.1	-3.7	-16	6.9
T	-2.2	-3.5	-2.3	-1.2	-1.3	-2.3	-5.3	1.7

D = Datchet E = Egham T = Teddington

Table 4.9. Percent change in 5 and 95 percentile distributions for dissolved oxygen (% Sat.) under selected climate change scenarios using data from 1974.

SITE	CLIMATE CHANGE SCENARIO							
	1		2		3		4	
	5%	95%	5%	95%	5%	95%	5%	95%
D	-20	4.7	-22	6.7	1.5	0.2	-53	13
E	-15	1.8	-14	4.6	-14	-4.4	-18	12
T	3.0	0.0	3.0	0.0	1.7	0.0	2.1	0.0

D = Datchet E = Egham T = Teddington

Table 4.10. Percent change in 5 and 95 percentile distibutions for biological oxygen demand (mg/l) under selected climate change scenarios using data from 1974.

SITE	CLIMATE CHANGE SCENARIO							
	1		2		3		4	
	5%	95%	5%	95%	5%	95%	5%	95%
D	-1.5	-0.6	-4.1	-2.4	3.1	3.0	-10	-6.0
E	-0.9	-0.9	-2.7	-2.6	3.1	1.8	-8.9	-5.7
T	-0.7	-1.4	-1.4	-1.4	0.7	-0.2	-2.2	-1.3

D = Datchet E = Egham T = Teddington

Table 4.11. Percent change in 5 and 95 percentile distributions for dissolved oxygen concentration (mg/l) under selected climate change scenarios using data from 1975.

SITE	CLIMATE CHANGE SCENARIO							
	1		2		3		4	
	5%	95%	5%	95%	5%	95%	5%	95%
D	-84	-2.1	-84	-1.4	-63	-5.8	-91	-1.0
E	-30	-2.0	-28	-0.8	-20	-7.2	-35	1.0
T	-12	-4.4	-10	-3.9	-6.0	-4.4	-51	-6.7

D = Datchet E = Egham T = Teddington

Table 4.12. Percent change in 5 and 95 percentile distributions for dissolved oxygen (% Sat.) under selected climate change scenarios using data from 1975.

SITE	CLIMATE CHANGE SCENARIO							
	1		2		3		4	
	5%	95%	5%	95%	5%	95%	5%	95%
D	-83	0.0	-83	0.0	-62	-3.5	-91	0.0
E	-24	0.0	-23	0.0	-15	-4.0	-29	0.0
T	9.5	0.0	6.3	0.0	13	0.0	-30	0.0

D = Datchet E = Egham T = Teddington

Table 4.13. Percent change in 5 and 95 percentile values for biological oxygen demand (mg/l) under selected climate change scenarios using data from 1975.

SITE	CLIMATE CHANGE SCENARIO							
	1		2		3		4	
	5%	95%	5%	95%	5%	95%	5%	95%
D	-0.7	-1.1	-2.8	-2.0	3.6	1.4	-7.8	-4.2
E	-0.6	-1.8	-0.6	-1.8	0.0	-0.7	-1.7	-1.7
T	-0.4	-2.6	-0.4	0.4	-0.8	-7.3	0.8	18

D = Datchet E = Egham T = Teddington

Table 4.14. Percent change in 5 and 95 percentile distributions for dissolved oxygen concentration (mg/l) under selected climate change scenarios using data from 1976.

SITE	CLIMATE CHANGE SCENARIO							
	1		2		3		4	
	5%	95%	5%	95%	5%	95%	5%	95%
D	-85	-2.3	-85	-1.8	-67	-2.7	-89	0.3
E	-23	-2.9	-20	-1.5	-19	-2.7	-25	-1
T	-3.0	-3.7	-4.9	-3.7	0.4	-3.1	-35	-5.2

D = Datchet E = Egham T = Teddington

Table 4.15. Percent change in 5 and 95 percentile distributions for dissolved oxygen (% Sat.) under selected climate change scenarios using data from 1976.

SITE	CLIMATE CHANGE SCENARIO							
	1		2		3		4	
	5%	95%	5%	95%	5%	95%	5%	95%
D	-83	0.0	-83	0.0	-65	0.0	-89	0.0
E	-7.8	0.0	-4.8	0.0	-5.9	0.0	-11	0.0
T	4.0	0.0	1.6	0.0	5.7	0.0	-22	0.0

D = Datchet E = Egham T = Teddington

Table 4.16. Percent change in 5 and 95 percentile distributions for biological oxygen demand (mg/l) under selected climate change scenarios using data from 1976.

SITE	CLIMATE CHANGE SCENARIO							
	1		2		3		4	
	5%	95%	5%	95%	5%	95%	5%	95%
D	-1.0	-1.6	-1.5	-2.6	1.0	0.7	-4.6	-5.7
E	-1.6	-2.3	-2.1	-0.7	0.5	-3.8	-6.7	4.0
T	-3.2	-3.5	-0.4	0.9	-4.9	-8.3	11	25

D = Datchet E = Egham T = Teddington

Table 4.17. Percent change in 5 and 95 percentile distributions for dissolved oxygen concentration (mg/l) under selected climate change scenarios using data from 1989.

SITE	CLIMATE CHANGE SCENARIO							
	1		2		3		4	
	5%	95%	5%	95%	5%	95%	5%	95%
D	-85	0.3	-85	2.3	-66	-3.2	-92	7.9
E	-57	-2.3	-57	-1.1	-36	-7.3	-72	-1.3
T	-45	-3.7	-47	-1.3	-15	-2.3	-87	-2.2

D = Datchet E = Egham T = Teddington

Table 4.18. Percent change in 5 and 95 percentile distributions for dissolved oxygen (% Sat.) under selected climate change scenarios using data from 1989.

SITE	CLIMATE CHANGE SCENARIO							
	1		2		3		4	
	5%	95%	5%	95%	5%	95%	5%	95%
D	-85	0.6	-85	3.0	-65	-4.6	-92	7.1
E	-55	-0.1	-55	0.0	-34	-6.3	-71	0.0
T	-25	0.0	-27	0.0	4.3	0.0	-85	0.0

D = Datchet E = Egham T = Teddington

Table 4.19. Percent change in 5 and 95 percentile distributions for biological oxygen demand (mg/l) under selected climate change scenarios using data from 1989.

SITE	CLIMATE CHANGE SCENARIO							
	1		2		3		4	
	5%	95%	5%	95%	5%	95%	5%	95%
D	-0.8	-1.9	-0.8	-4.2	-1.6	3.5	-1.6	-12
E	-1.5	-2.4	-0.8	-3.1	-0.8	1.5	-0.8	-5.3
T	-2.1	-3.1	0.0	1.3	-11	-9.2	4.8	21

D = Datchet E = Egham T = Teddington

Table 4.20 Changes in water quality class under extreme scenarios from the original (as specified by the % saturation of dissolved oxygen).

	WATER QUALITY CLASS		
	ORIGINAL	SCENARIO 3	SCENARIO 4
1974			
Datchet	1B	1B	3
Egham	1A	1B	1B
Teddington	1A	1A	1A
1975			
Datchet	2A	3	<3
Egham	2A	2A	2A
Teddington	1B	1A	2A
1976			
Datchet	<3	<3	<3
Egham	1A	1A	1B
Teddington	1A	1A	1B
1989			
Datchet	<3	<3	<3
Egham	1B	2A	3
Teddington	1A	1A	3

CHAPTER FIVE

CONCLUSIONS AND FUTURE RESEARCH

Flow and eight water quality parameters for four years (1974,1975,1976 and 1989) have been modelled using the multi-reach water quality network model, QUASAR. Four climate change scenarios have been applied to this data, and the impacts on the water quality parameters assessed.

The only significant changes in the water quality variables observed under the climate change scenarios applied were for dissolved oxygen and biochemical oxygen demand. The changes in these variables were largely governed by the annual algal growth pattern, so that at the end of the summer months the % saturation of DO was particularly reduced, and BOD correspondingly increased.

Under the temperatures and evapotranspiration rates envisaged, by global climate models, to be likely in the year 2050, the in-stream % saturation of dissolved oxygen will decline. Change in this parameter alone is sufficient to lower the water quality classification of the lower reaches of the Thames (Table 4.20).

This deterioration in water quality will have serious implications for the National Rivers Authorities if they are to continue to maintain and improve the classification of the

lower Thames. Obviously this will require capital expenditure and resource investment, e.g. in upgrading sewage treatment works as natural dilution from reduced flows diminishes, and dealing with increased algae problems. In addition future policies for discharge consents may have to be reassessed in light of this climate change impact and possible resource demand changes.

In the future, it will be valuable to calibrate and validate QUASAR for catchments other than the Thames. Unregulated lowland and upland catchments in particular will, with different water chemistry and flow hydraulics and regimes, no doubt show the impacts of climate change to be different from that observed in the Thames. Modelling land use changes in conjunction with climatic changes will be a worthwhile exercise, as in the long term, the reliance of land use on climate is obvious.

Additional parameters may be incorporated into QUASAR, as and when the demand arises. At present, there are intentions to improve the modelling of *E. coli* by incorporating growth processes into the model. Applications to agricultural catchments may instigate the modelling of pesticides as and additional feature.

The algae processes modelled by QUASAR may be extended to account for the annual growth and death cycles, and their impact on oxygen dynamics. Currently, the input chlorophyll-a

concentrations are maintained throughout the year. This addition would be a valuable asset as algal blooms have become an increasing concern in water quality.

QUASAR is to be developed to run on an IBM PC which may make the model available for wider use, and the cost more competitive. Adjustments in data handling could create a more user-friendly model; multiple parameter and graphics outputs would enable easier interpretation of model results.

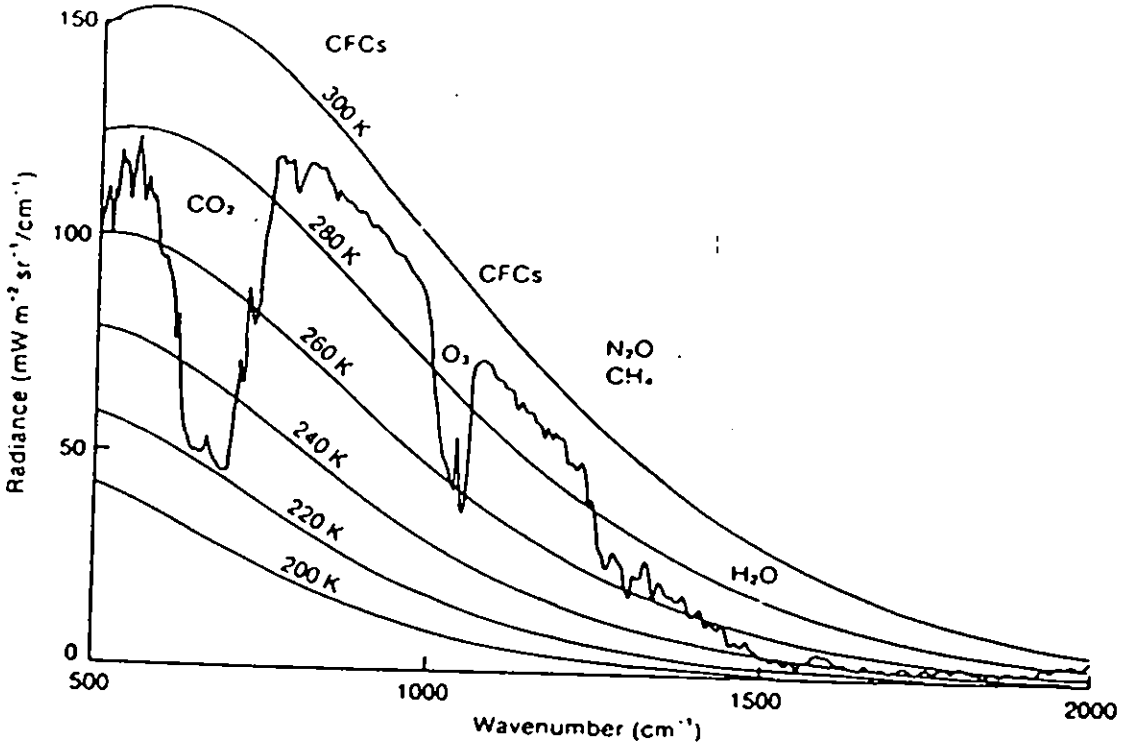


Figure 2.1. Atmospheric emission spectrum obtained from 33.5km above Palestine, Texas, May 1966 using a balloon-borne IRIS breadboard instrument (Rowntree 1990).

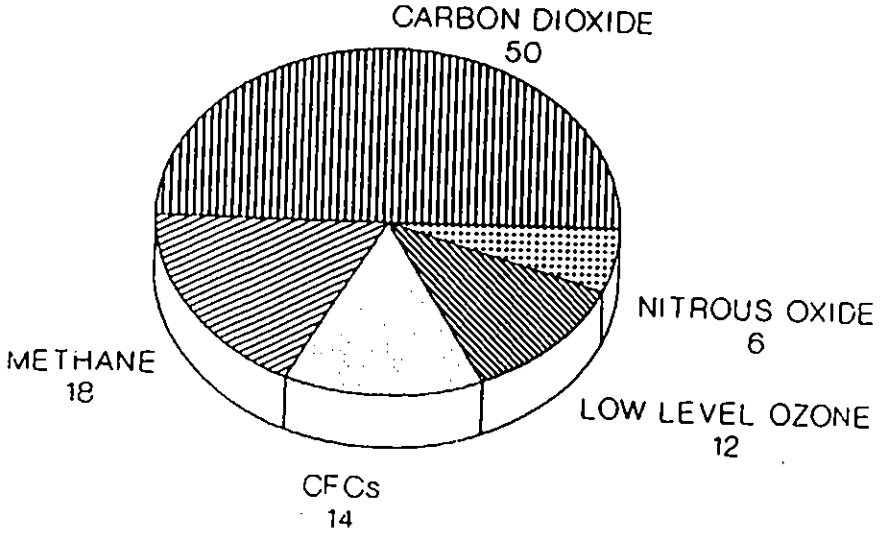


Figure 2.2. The relative contributions of individual greenhouse gases to global warming in the 1980s (Doornkamp 1989).

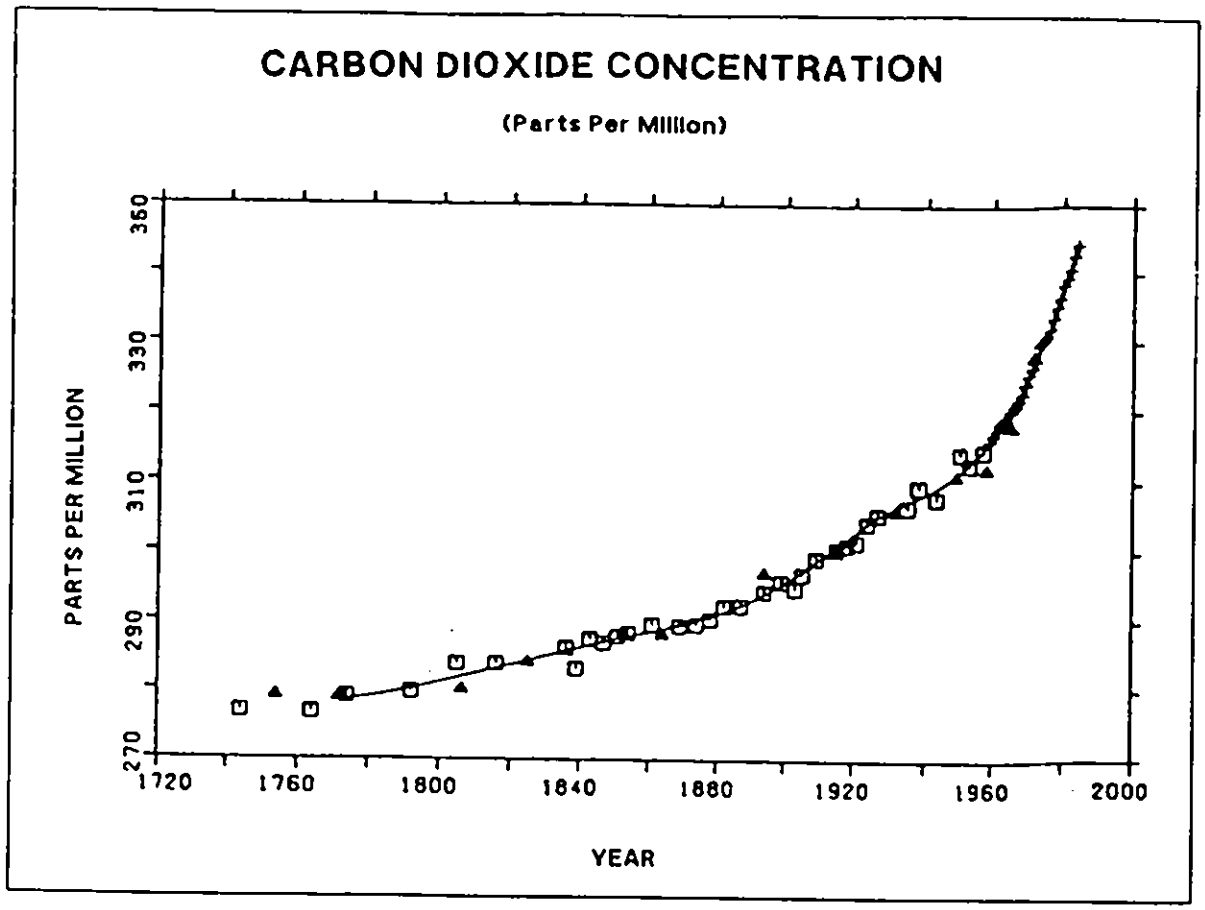


Figure 2.3. The history of atmospheric CO_2 presented here is based on ice core measurements (open spaces, closed triangles) and atmospheric measurements (crosses). The data show that CO_2 began to increase in the 1800s with the conversion of forests to agricultural land. The rapid rise since the 1950s, due primarily to fossil fuel combustion, is at a rate unprecedented in the ice core record (Lashof & Tirpak 1991).

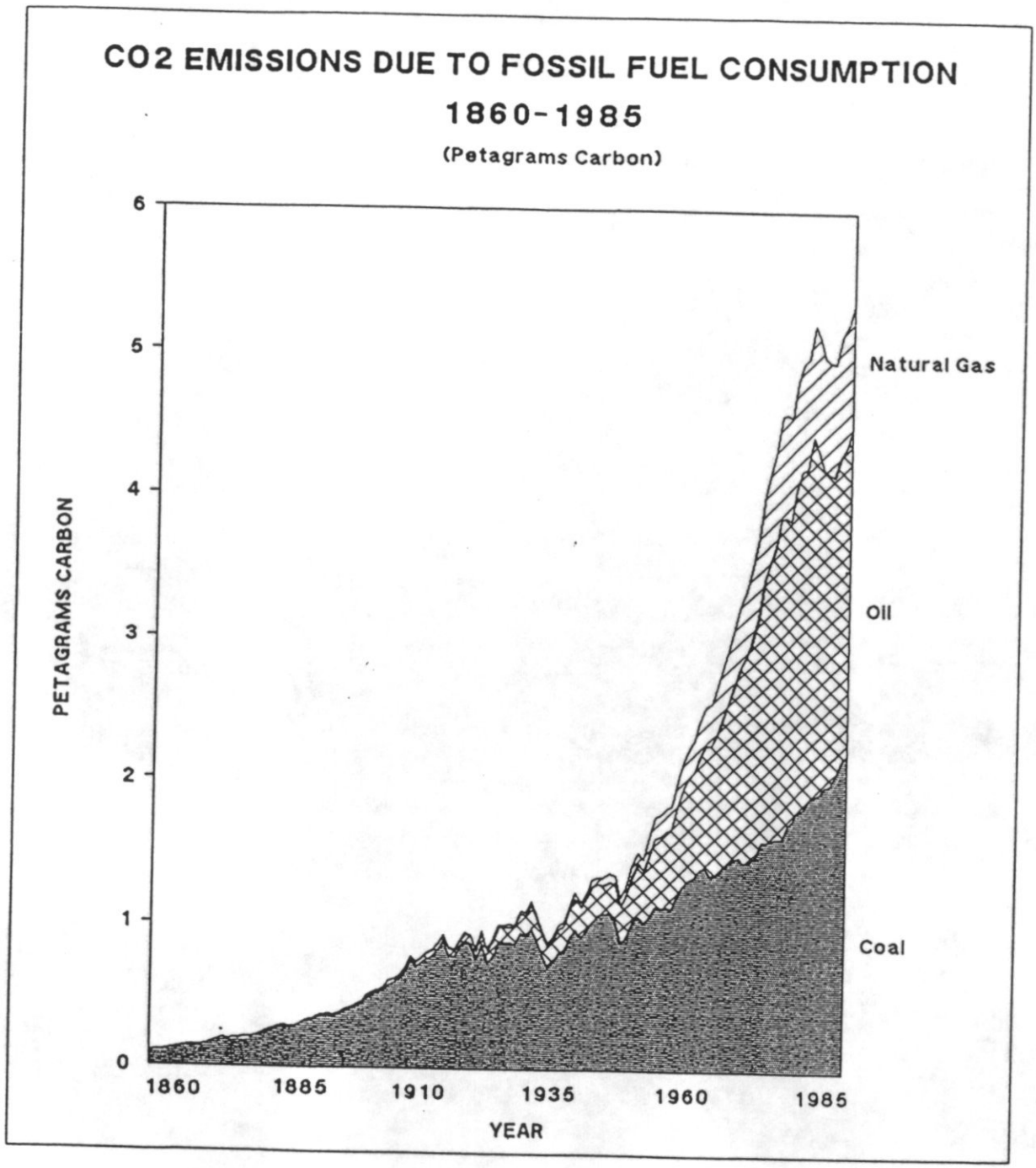


Figure 2.4. Carbon dioxide emissions from fossil fuel combustion have grown from less than 0.1 Pg C in the mid-1850s to approximately 5.4 Pg C in 1986. This is the major reason why the atmospheric concentration of CO_2 increased from approximately 290 ppm in 1860 to approximately 348 ppm in 1987 (Lashof & Tirpak 1991).

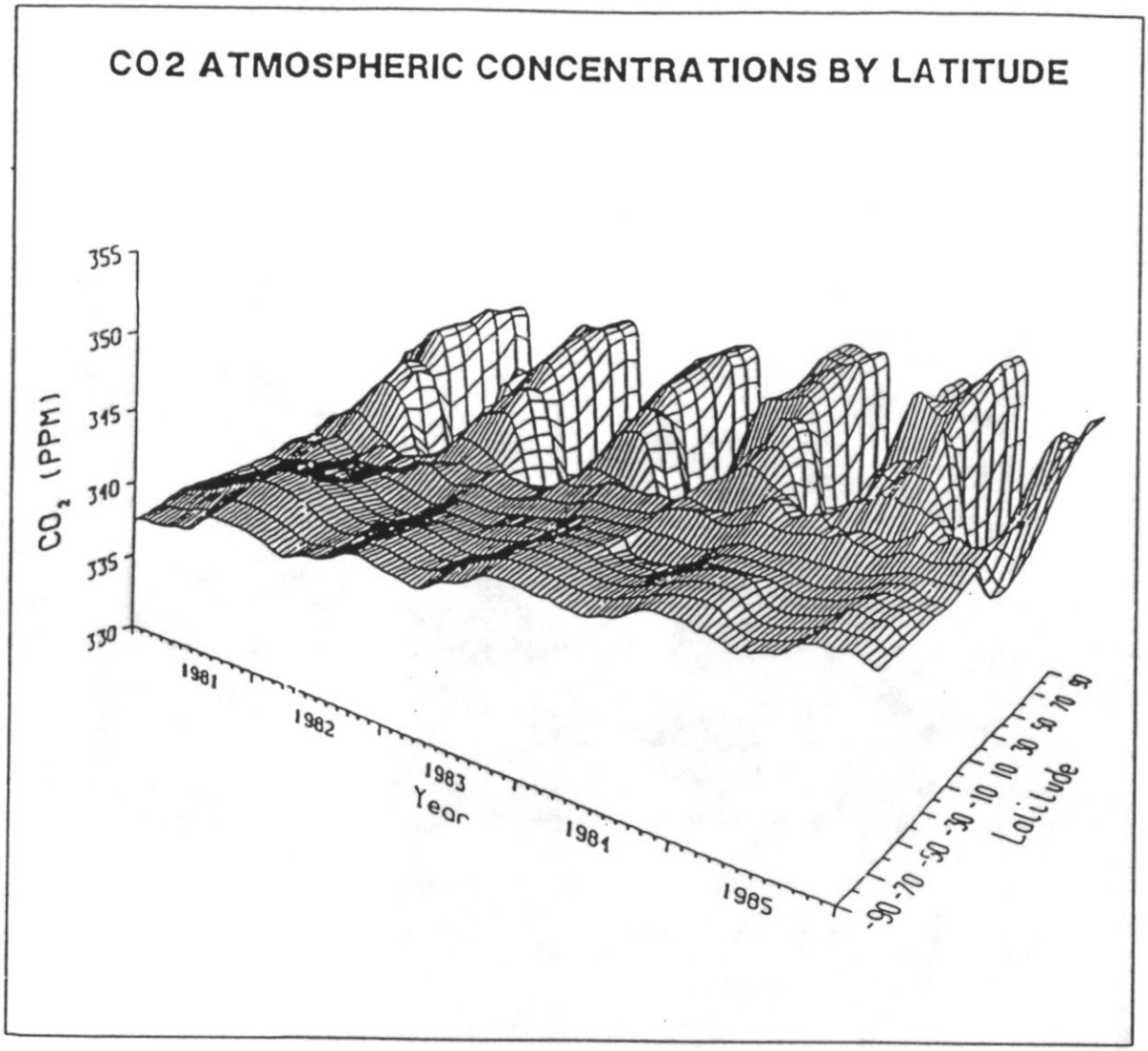


Figure 2.5. The distribution of CO_2 by latitude from 1981-1985 shows that CO_2 is increasing globally. Superimposed on the increasing trend are coherent seasonal oscillations reflective of seasonal dynamics of terrestrial vegetation. The seasonal cycle is strongest in the high Northern latitudes, and is weak and of opposite phase in the Southern Hemisphere, reflecting the distribution of terrestrial vegetation (Lashof & Tirpack).

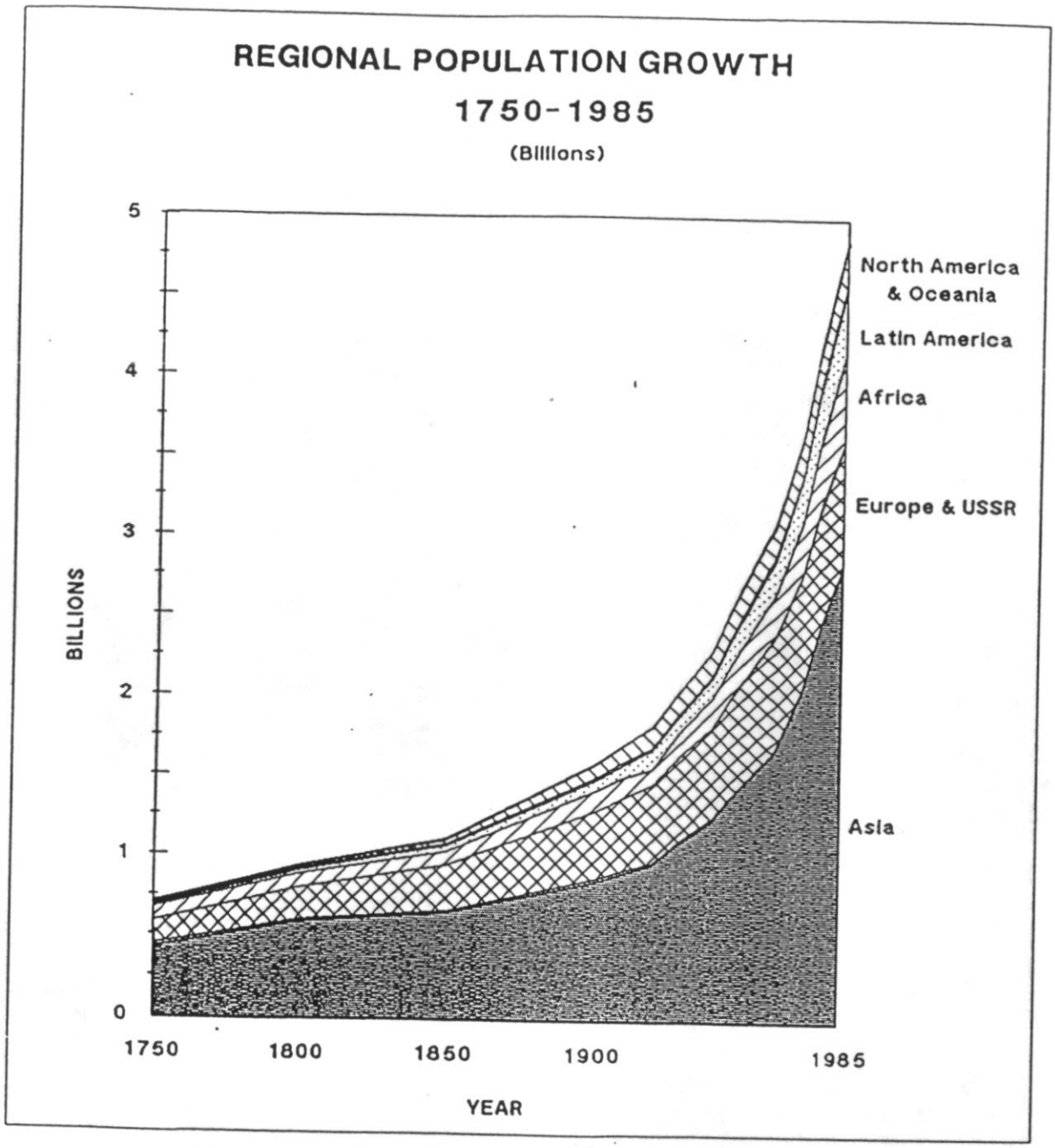


Figure 2.6. Since about 1850, global population has grown at increasingly rapid rates. In 1850, the population doubling time was approximately 200 years; by 1975, the doubling time had declined to approximately 45 years. Most of the growth has occurred in the developing world, particularly Asia (Lashof & Tirpak 1991).

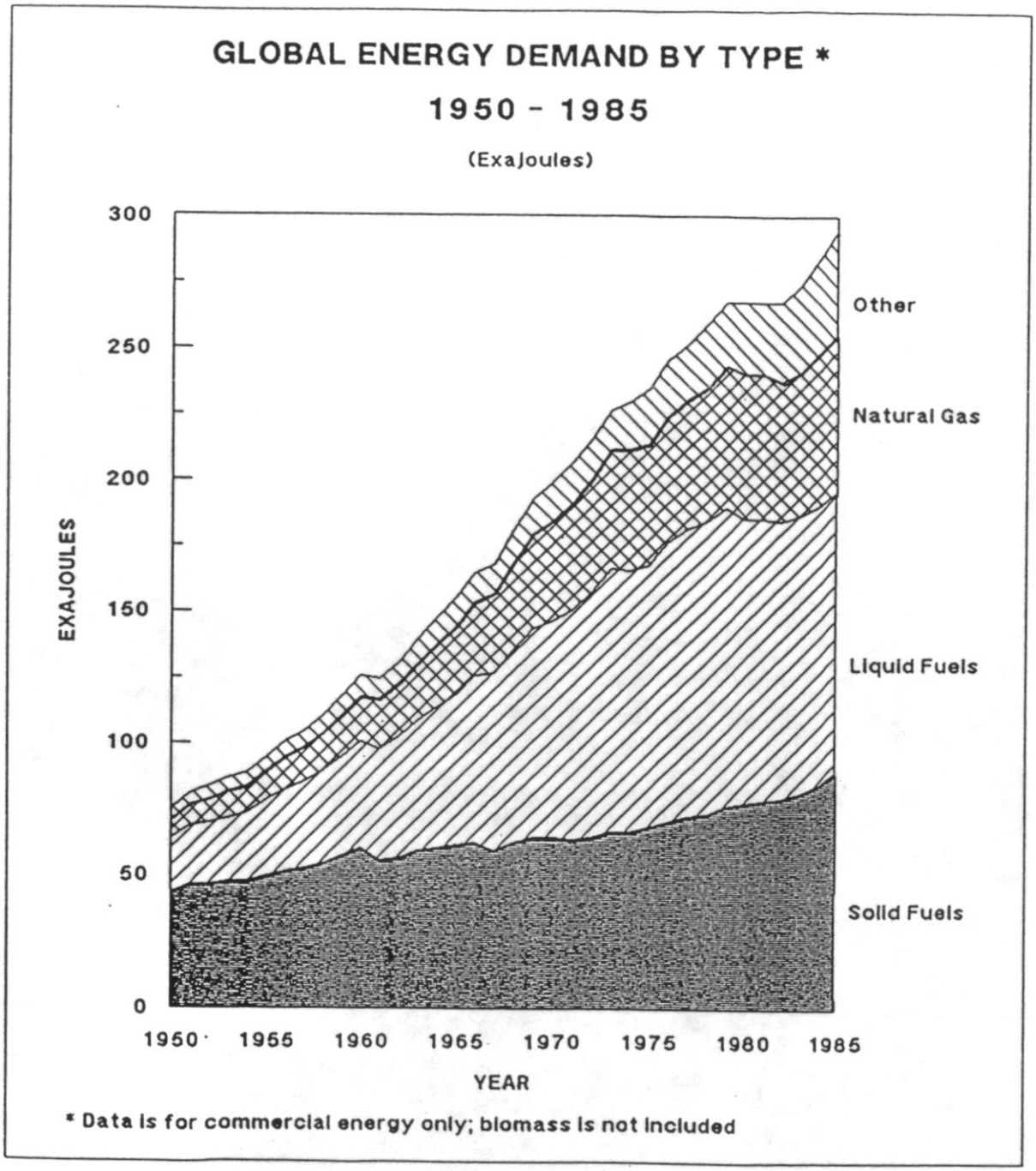


Figure 2.7. Global demand for fossil fuels has more than tripled since 1950. Today, about 85% of the world's energy needs are net by fossil fuels (Lashof & Tirpak).

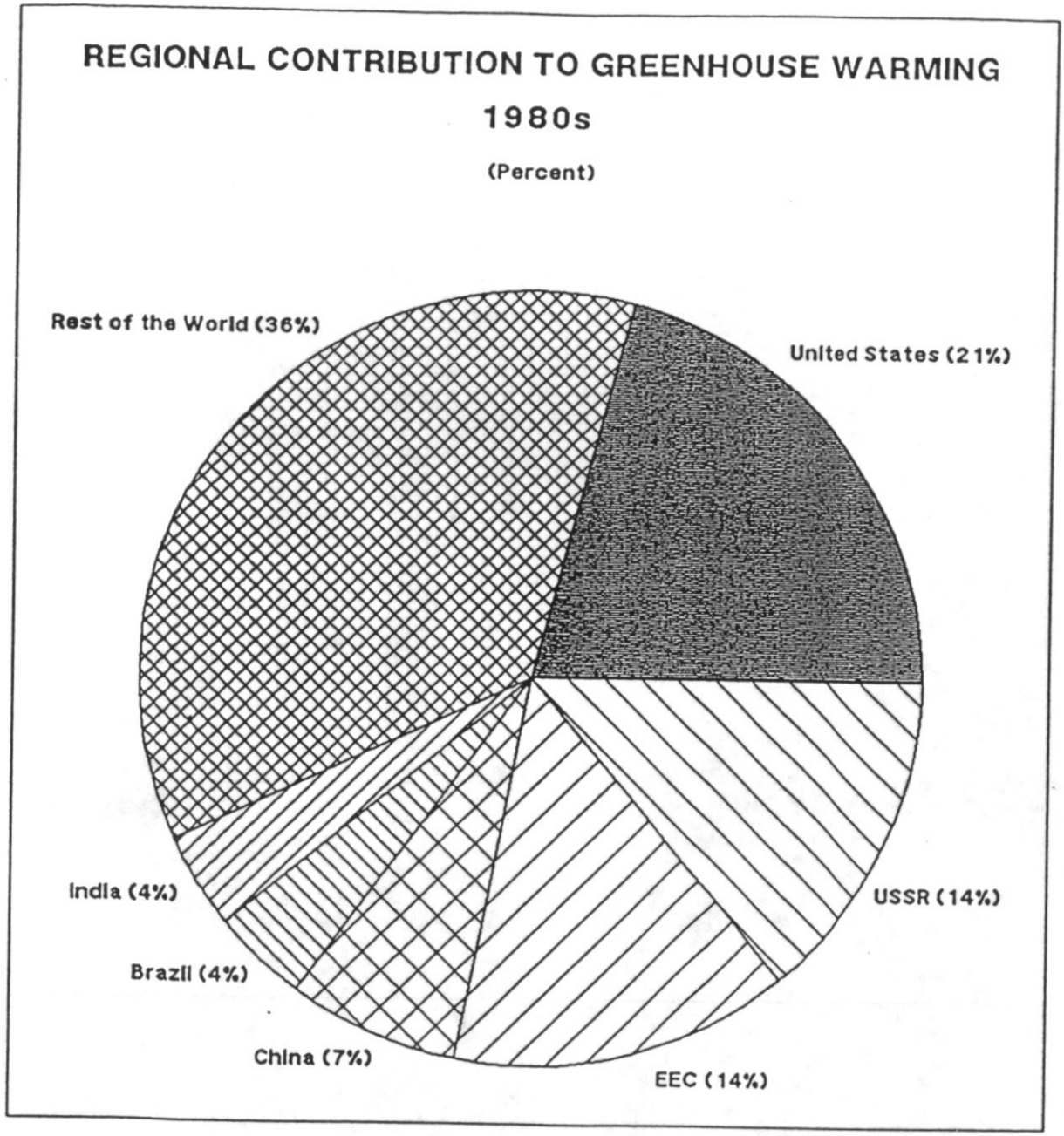


Figure 2.8. Estimated regional contribution to greenhouse warming for the 1980s, based upon regional shares of current levels of human activities that contribute to greenhouse gas emissions (Lashof & Tirpak).

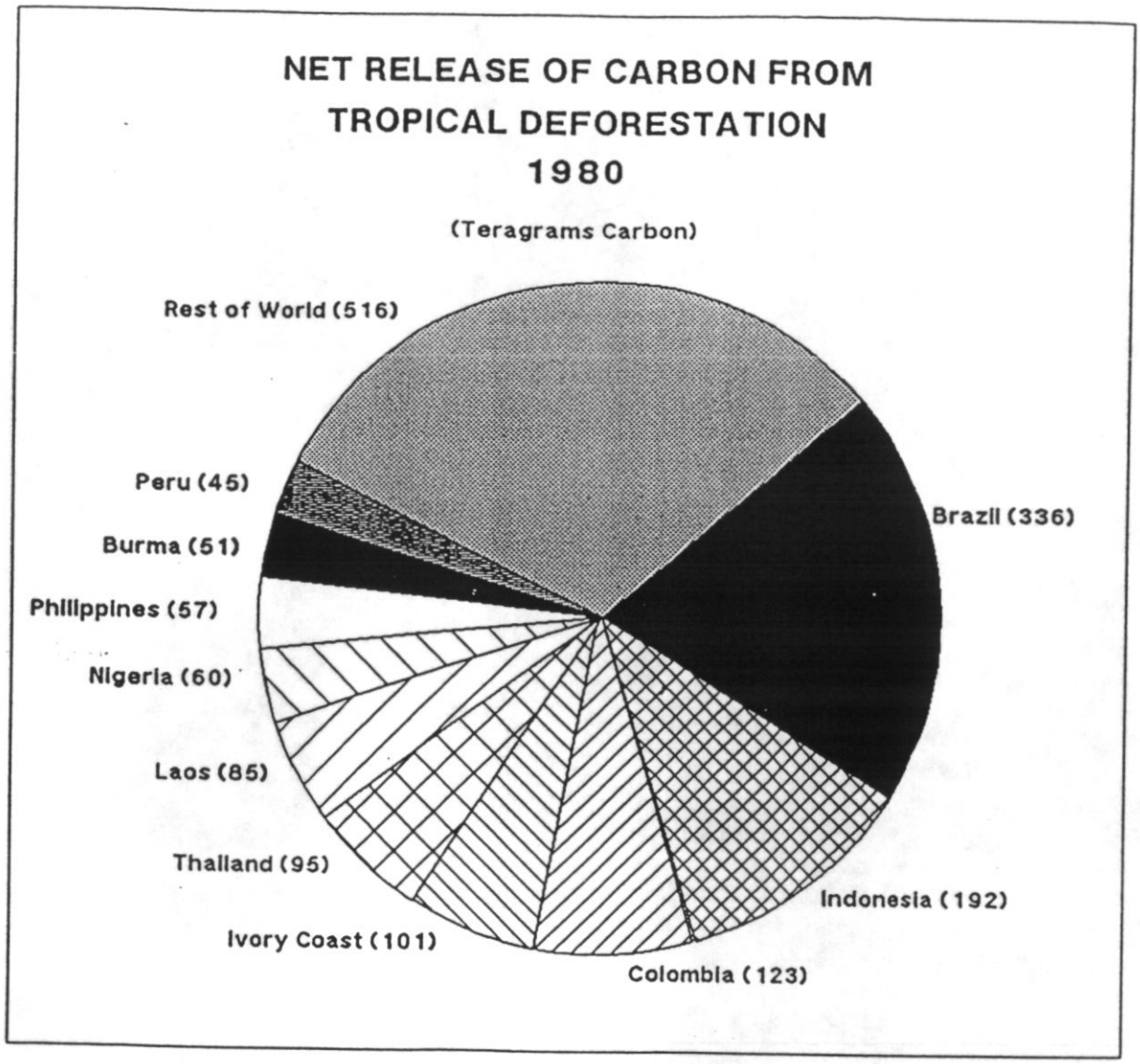


Figure 2.9. Tropical deforestation accounts for approximately 10-30% of the annual anthropogenic CO_2 emissions to the atmosphere. Over half of the 1980 CO_2 emissions from deforestation was produced by six countries: Brazil, Indonesia, Columbia, the Ivory Coast, Thailand, and Laos (Lashof & Tirpak).

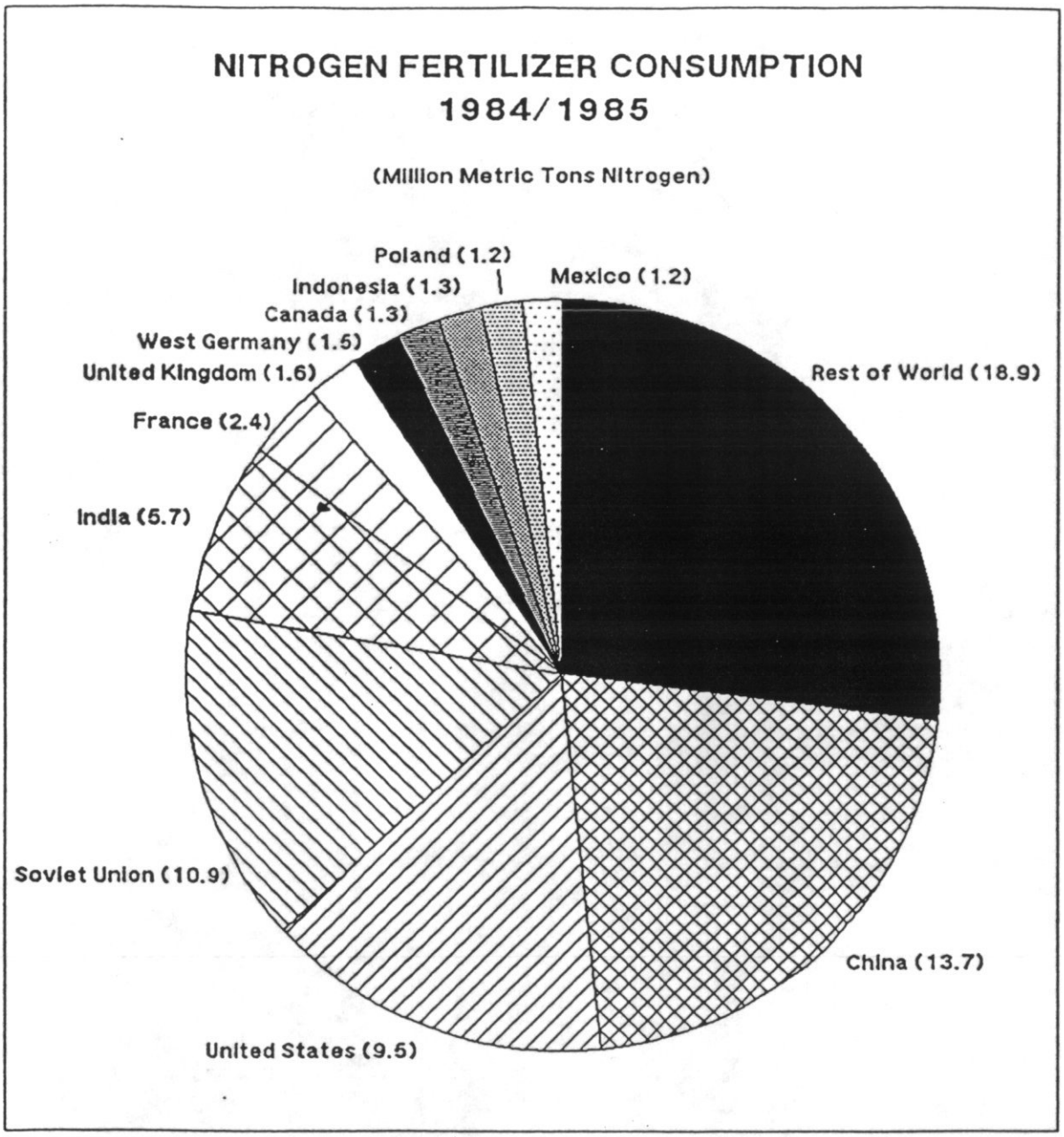


Figure 2.10. Distribution of the total nitrogenous fertilizer consumption of 70.5 million tons N. China, the United States, and the Soviet Union together accounted for just over 50% of the 1984/1985 global fertilizer consumption. Currently, 5-35% of the total anthropogenic N_2O emissions are attributed to nitrogenous fertilizer consumption (Lashof & Tirpak).

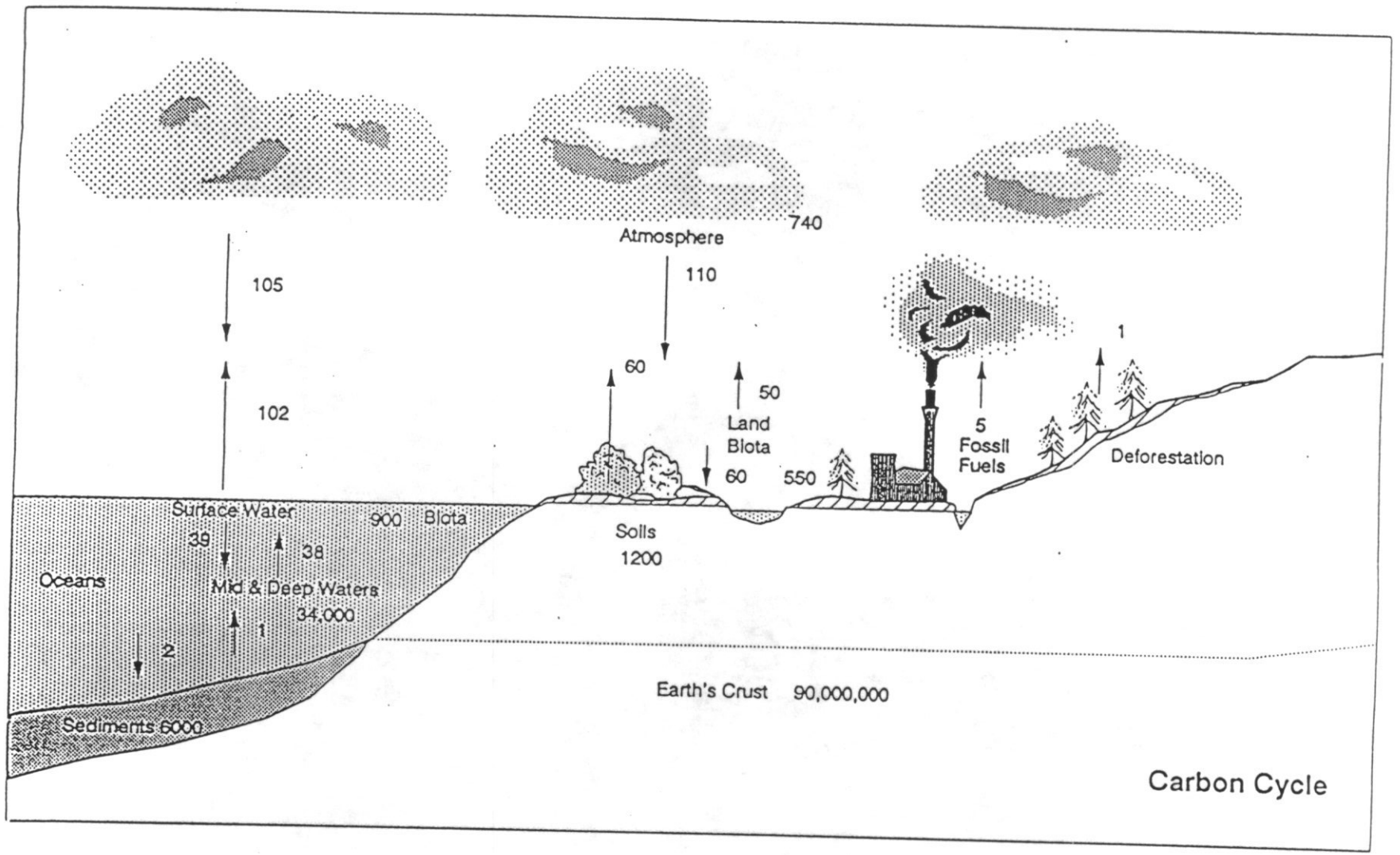


Figure 2.11. The carbon cycle showing the estimated carbon content of the principal reservoirs and the annual fluxes between them in units of 10^{12} Kg.

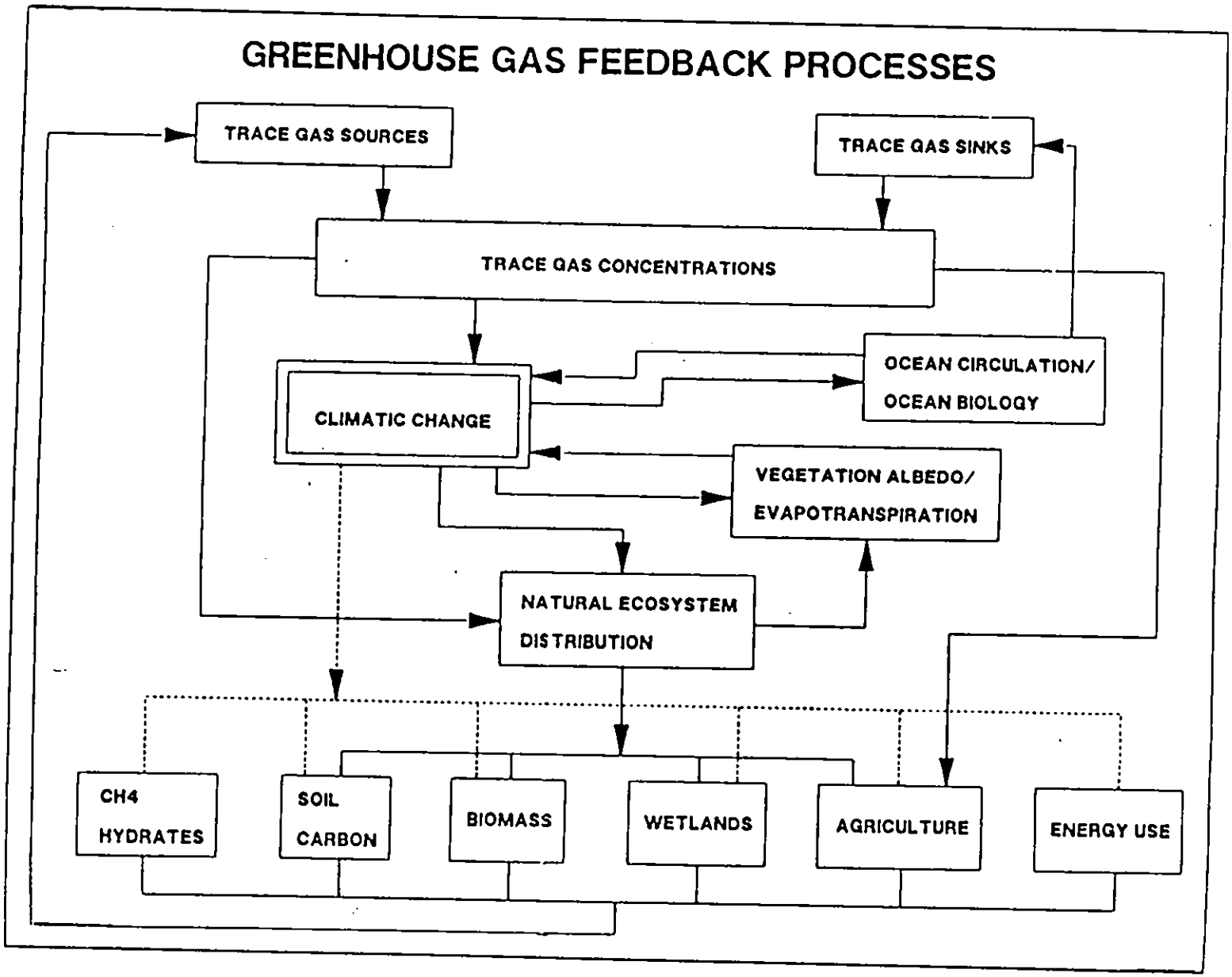


Figure 2.12. Flow diagram illustrating greenhouse gas feedback processes (Lashof & Tirpak).

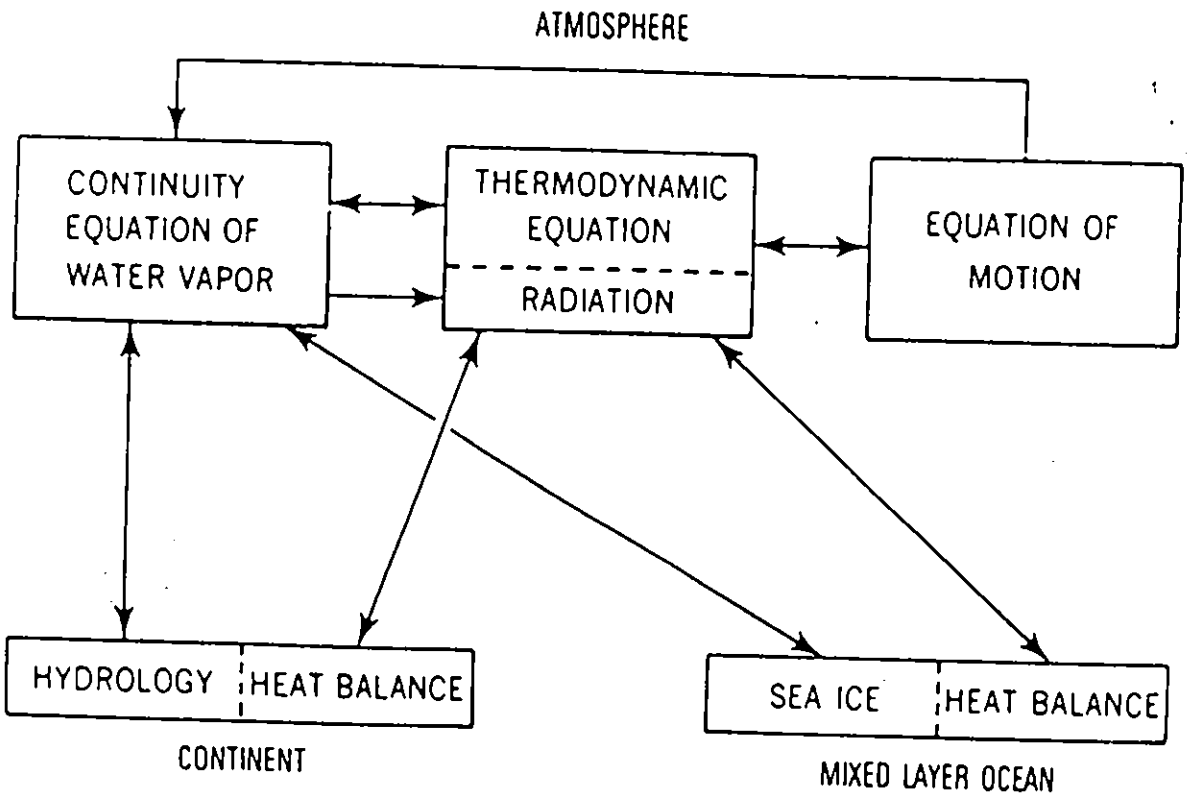


Figure 2.13. Box diagram to show the structure of a typical Global Climate Model (Hartmann, 1990).

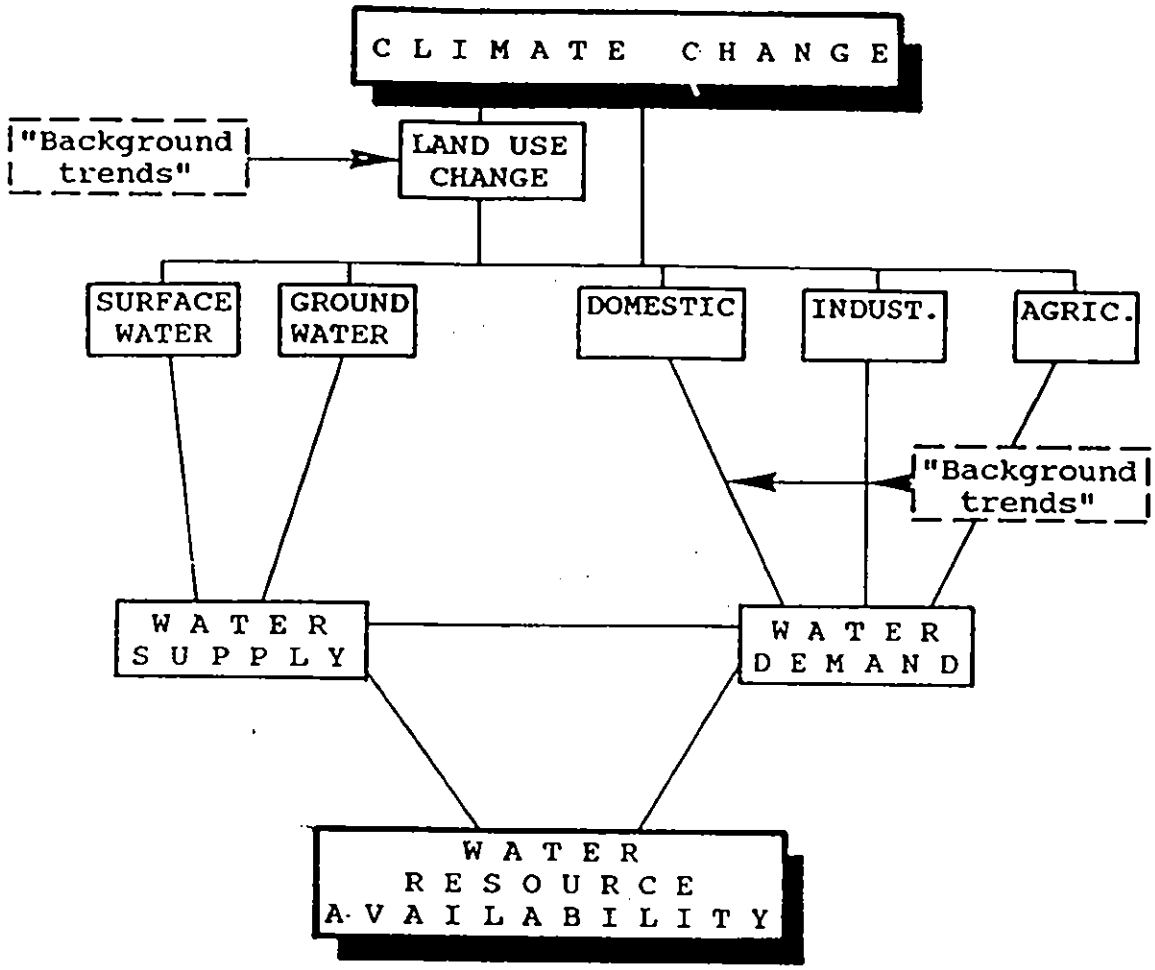


Figure 2.14. Key inter-relationships between climate change and water supply, demand and resource availability.

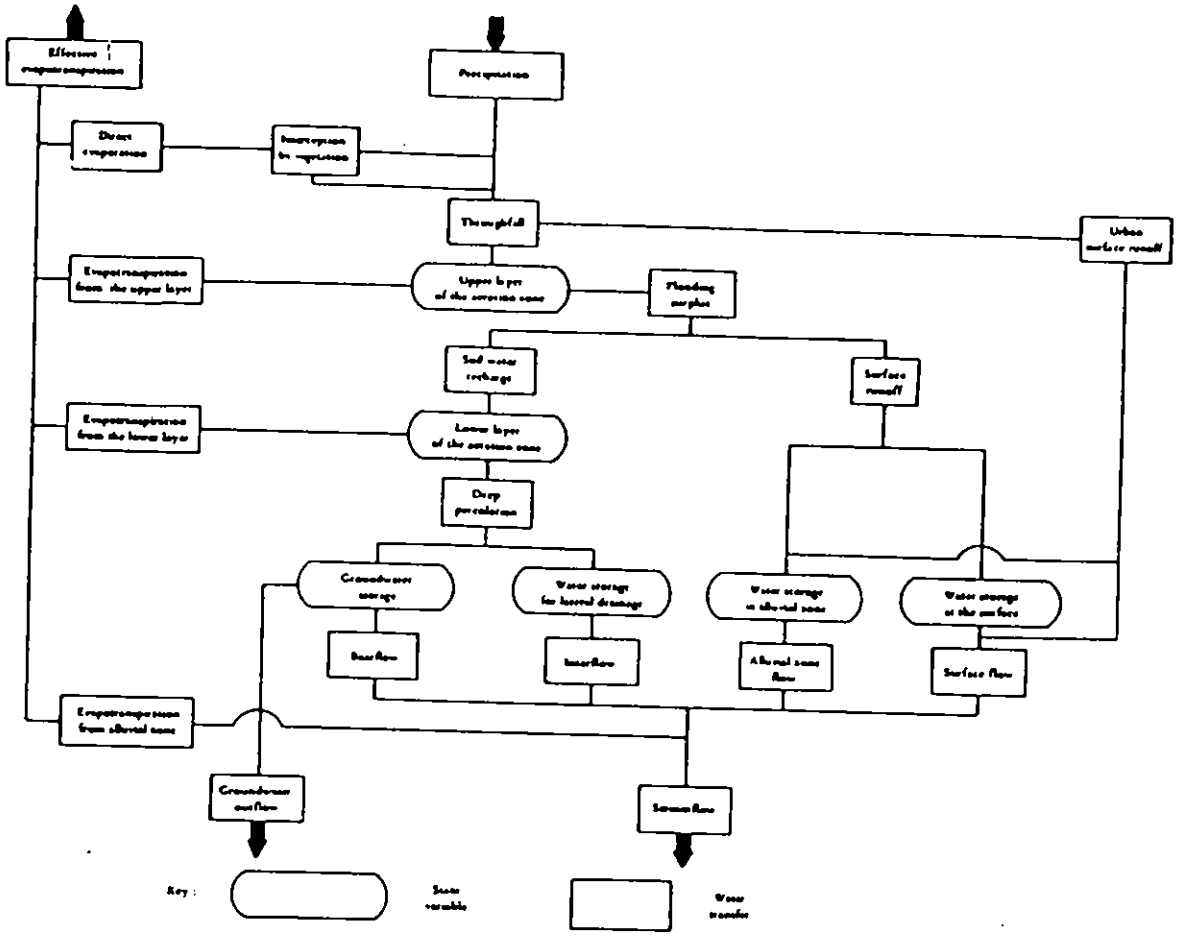


Figure 2.15. Flow chat of the IRBM model (Bultot *et al.*, 1988; 1989).

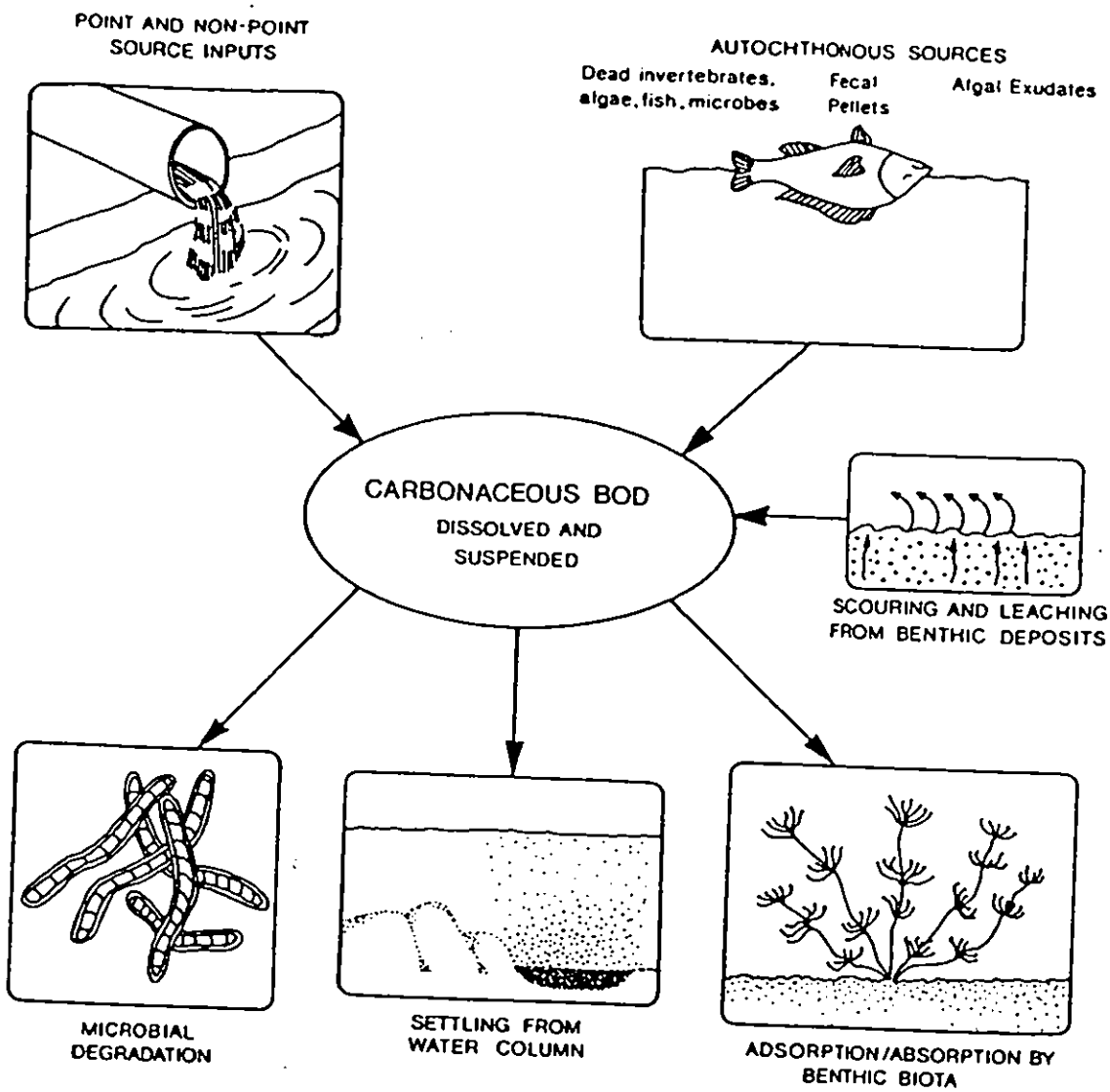


Figure 2.16. Major sources and sinks of carbonaceous BOD in streams.

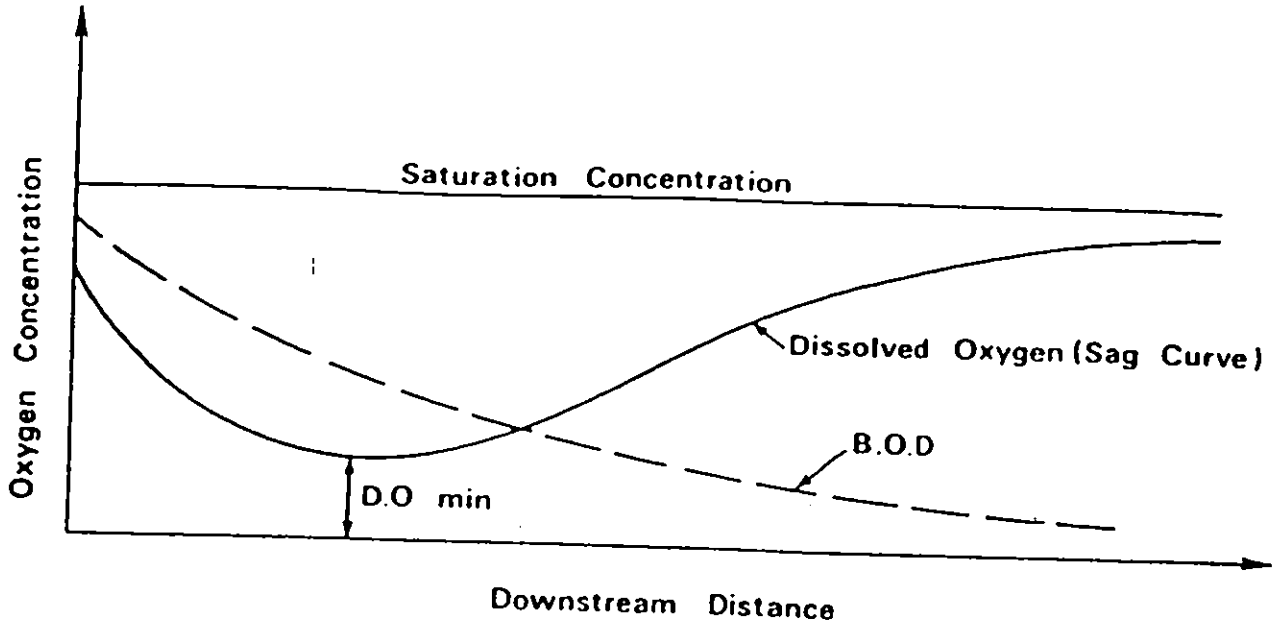


Figure 2.17. The oxygen sag curve.

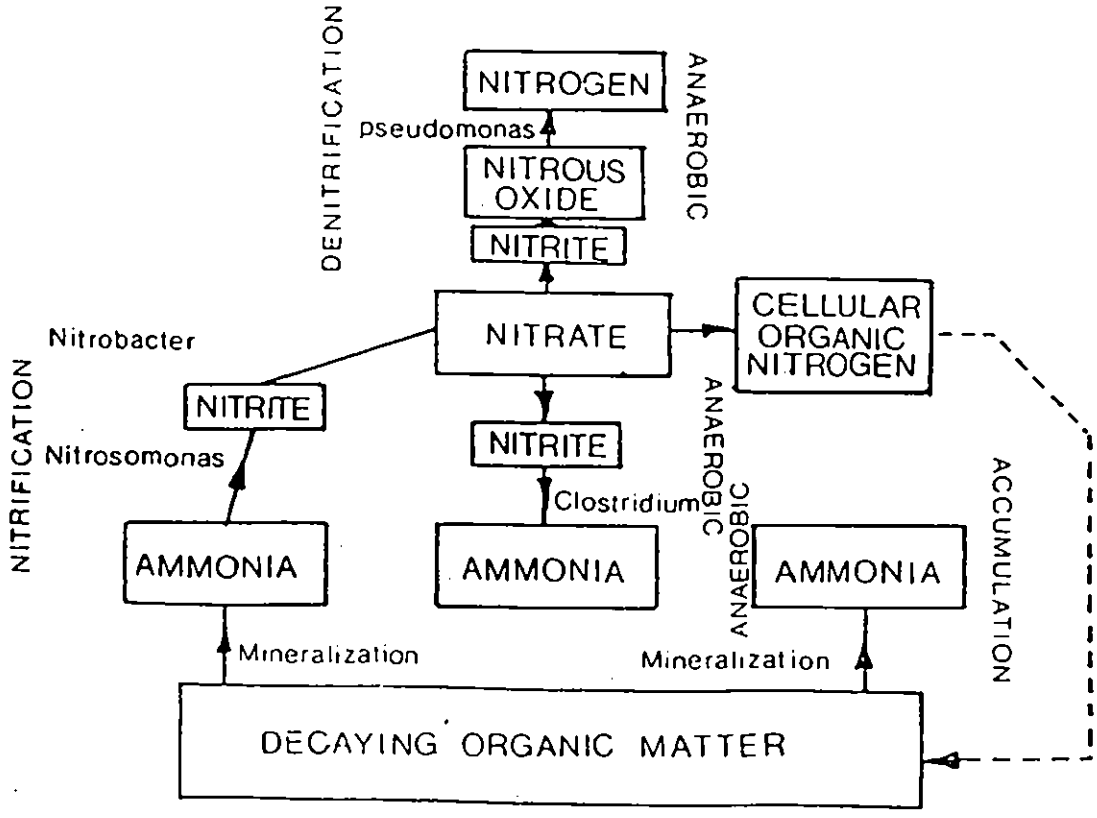


Figure 2.18. Nitrogen transformations in river systems.

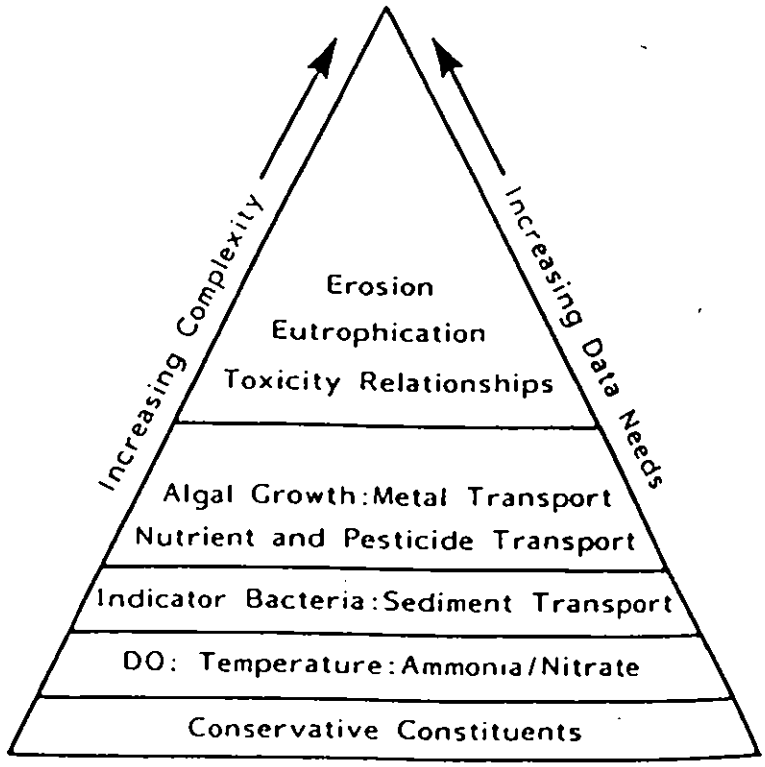


Figure 2.19. Relative difficulty of applied modelling (Hines *et al.*, 1974).

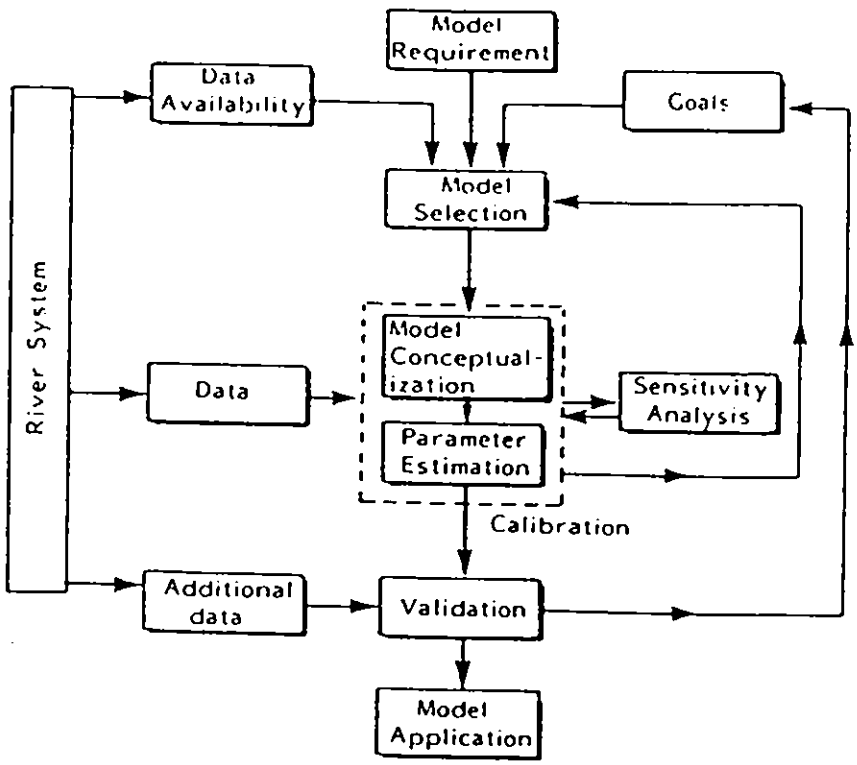


Figure 2.20. Illustration of modelling procedure (Crabtree *et al.*, 1987).

Figure 3.1. The Thames catchment.

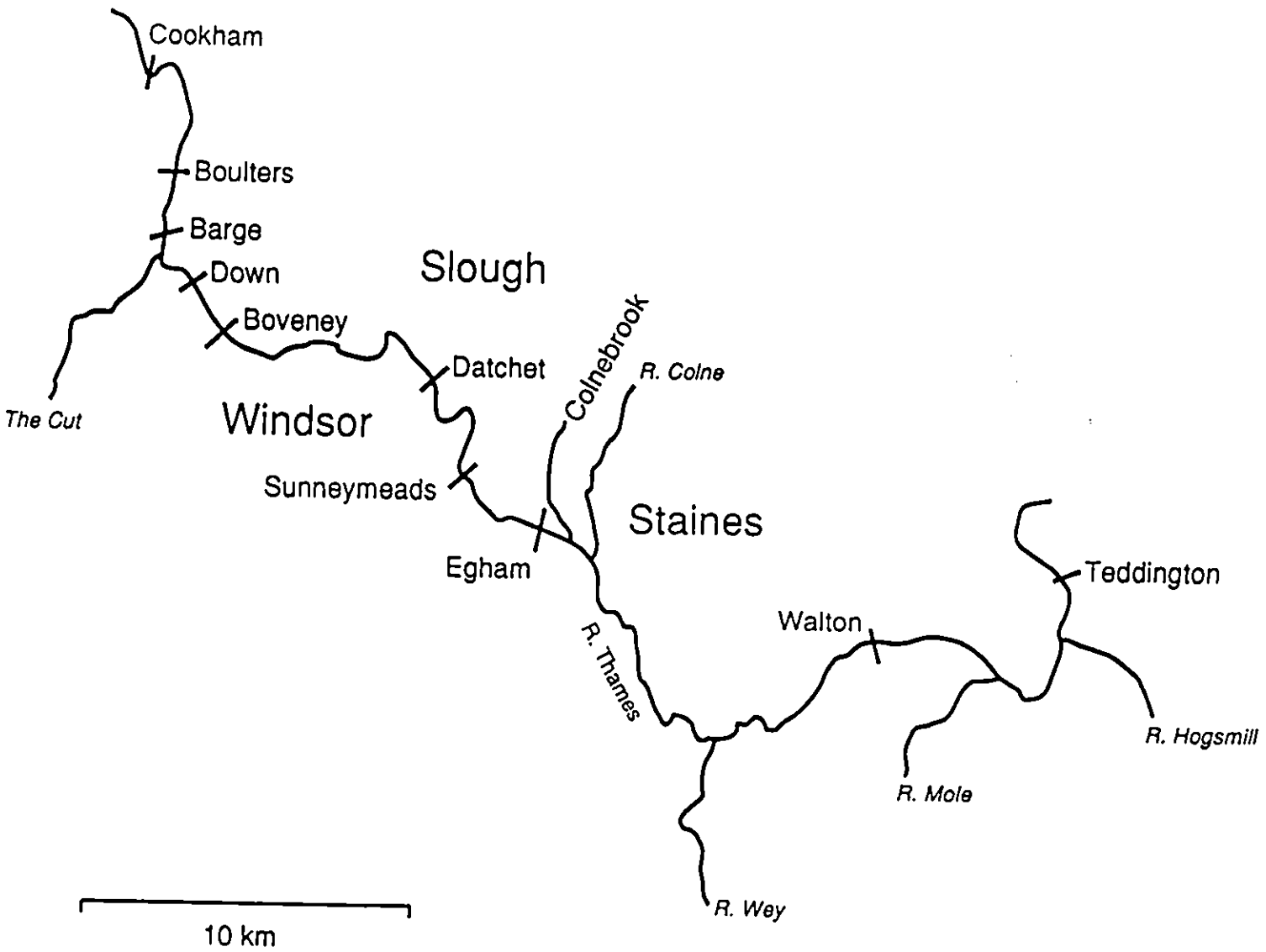
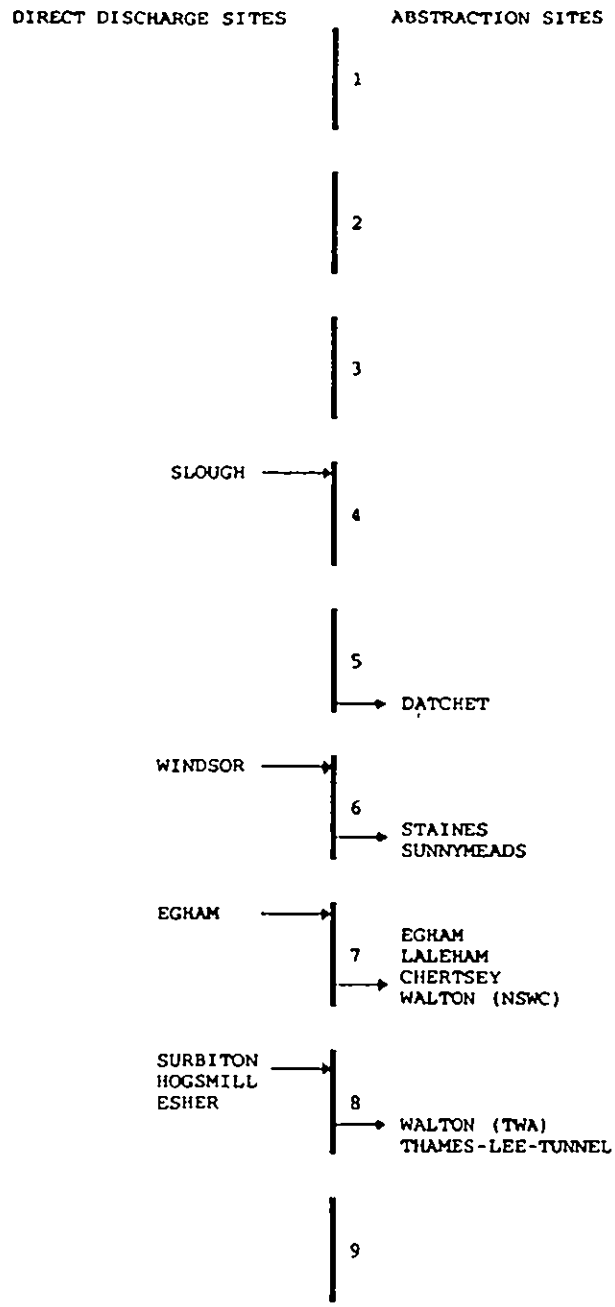


Figure 3.2. The Thames study site from Cookham to Teddington.



Reaches:

1: Cookham to Boulter
2: Boulter to Barge
3: Barge to Down
4: Down to Boveney
5: Boveney to Datchet
6: Datchet to Sunnymeads
7: Sunnymeads to Egham
8: Egham to Walton
9: Walton to Teddington

Figure 3.3. Reach structure for the study site from Cookham to Teddington.

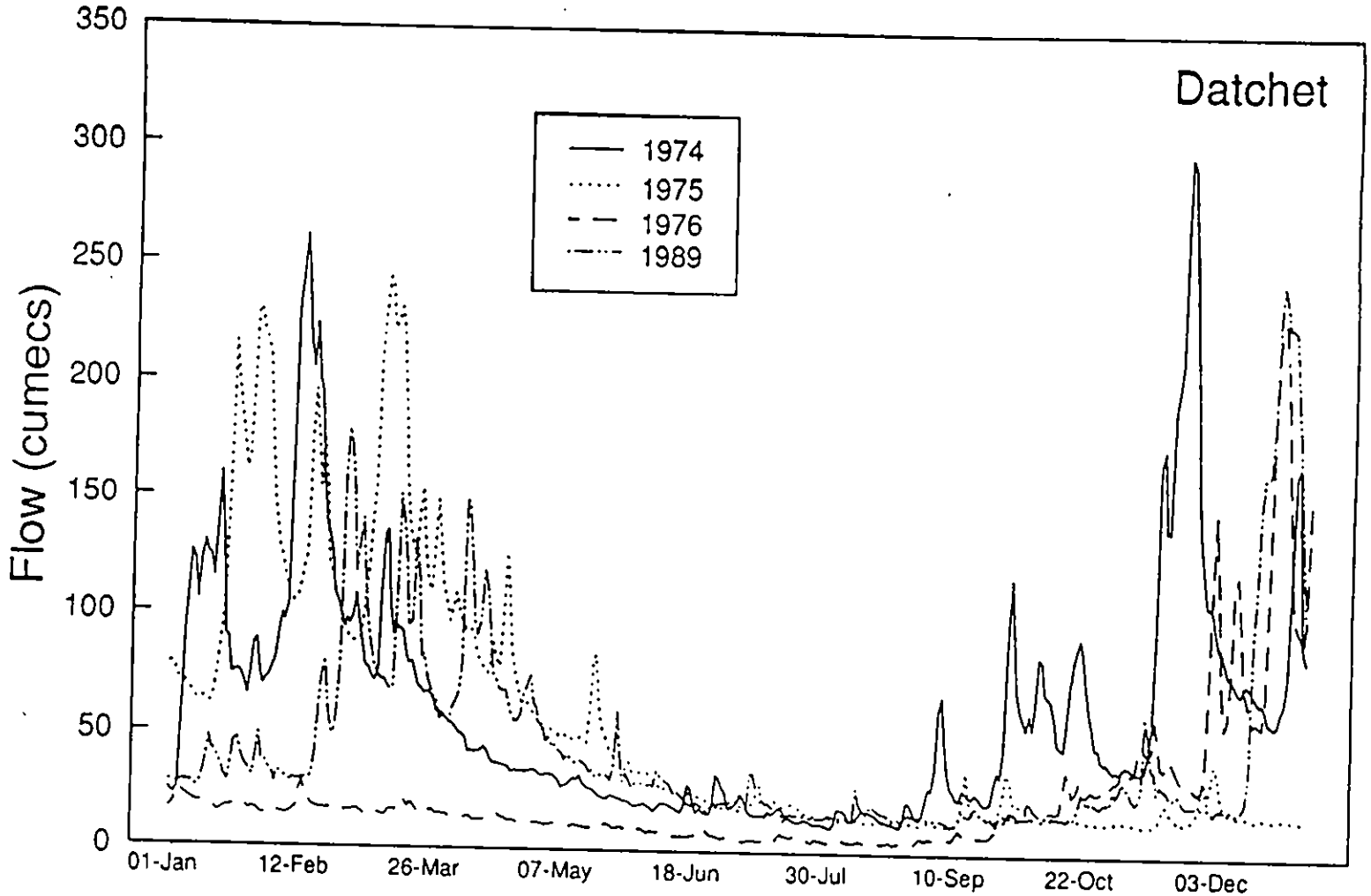


Figure 4.1a. Original flow at Datchet.

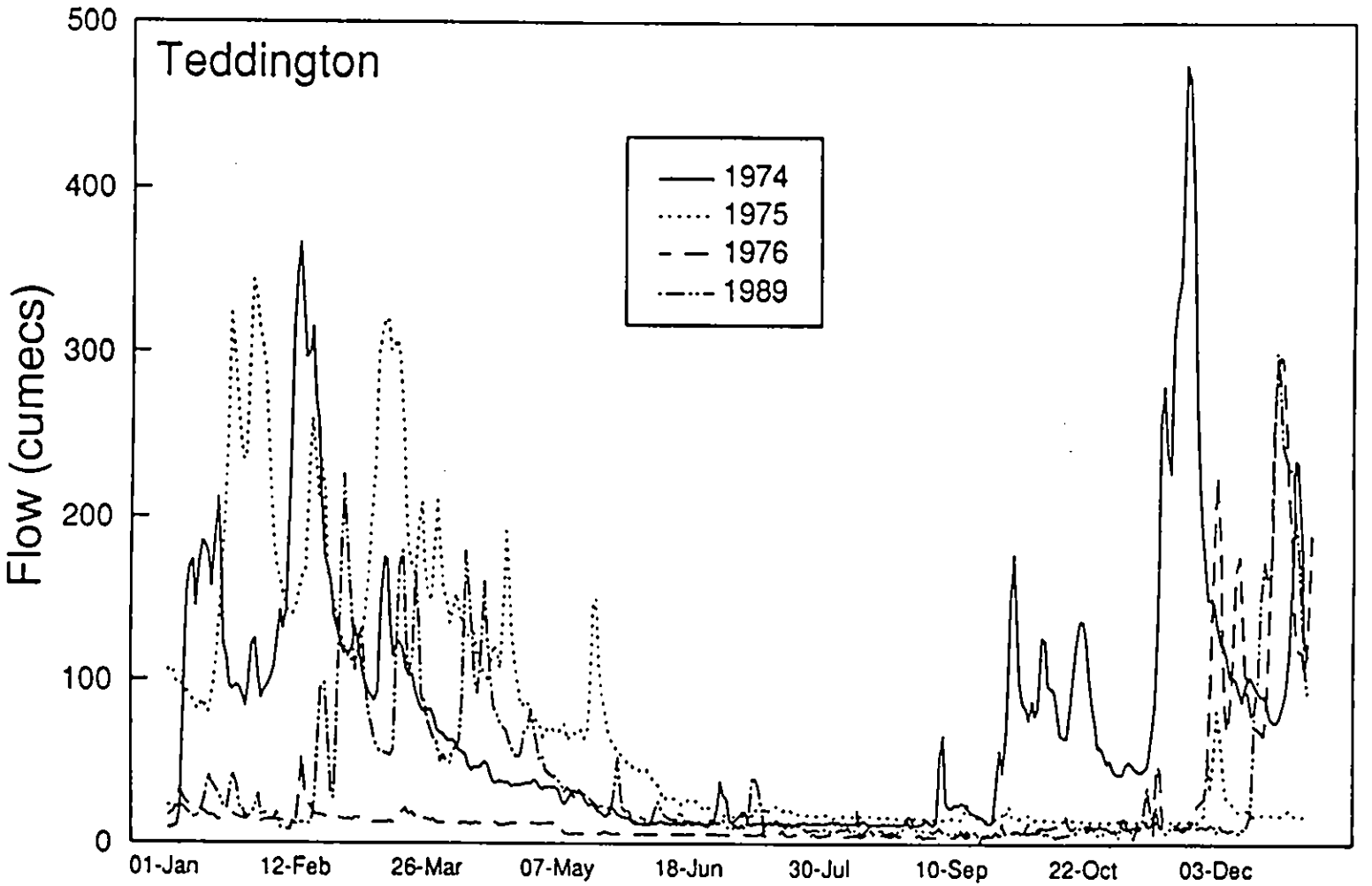


Figure 4.1b. Original flow at Teddington.

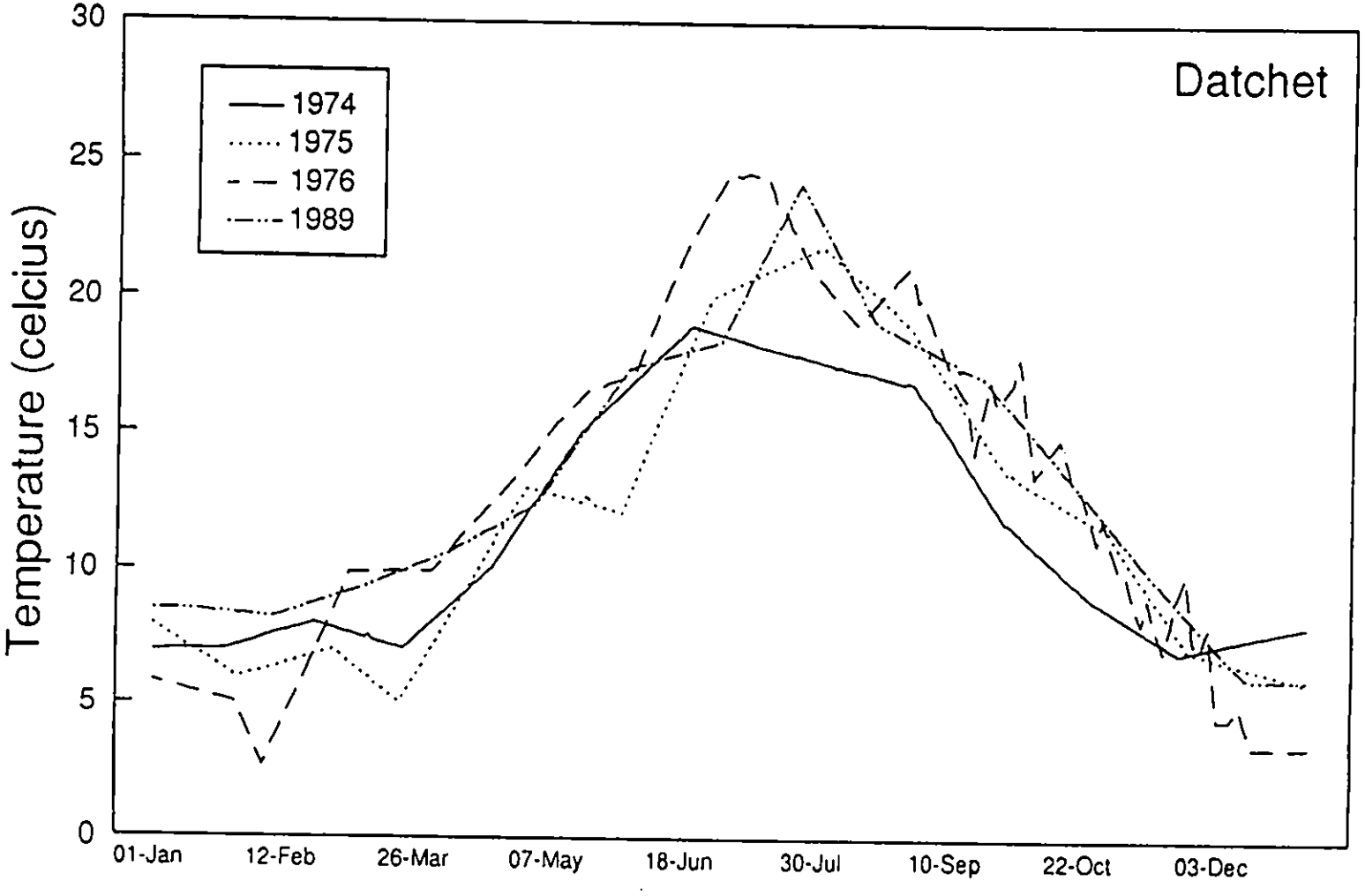


Figure 4.2a. Original temperature at Datchet.

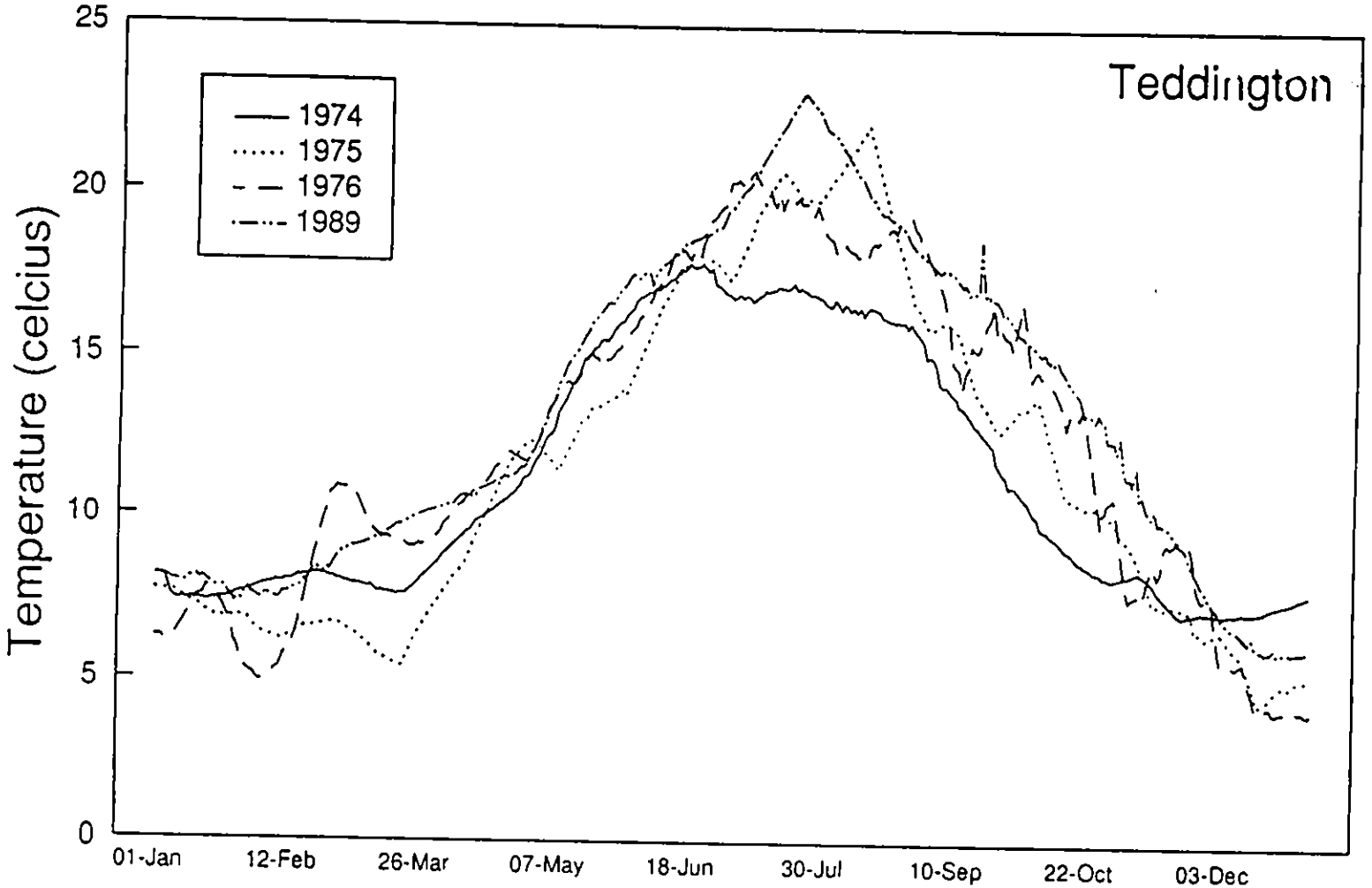


Figure 4.2b. Original temperature at Teddington.

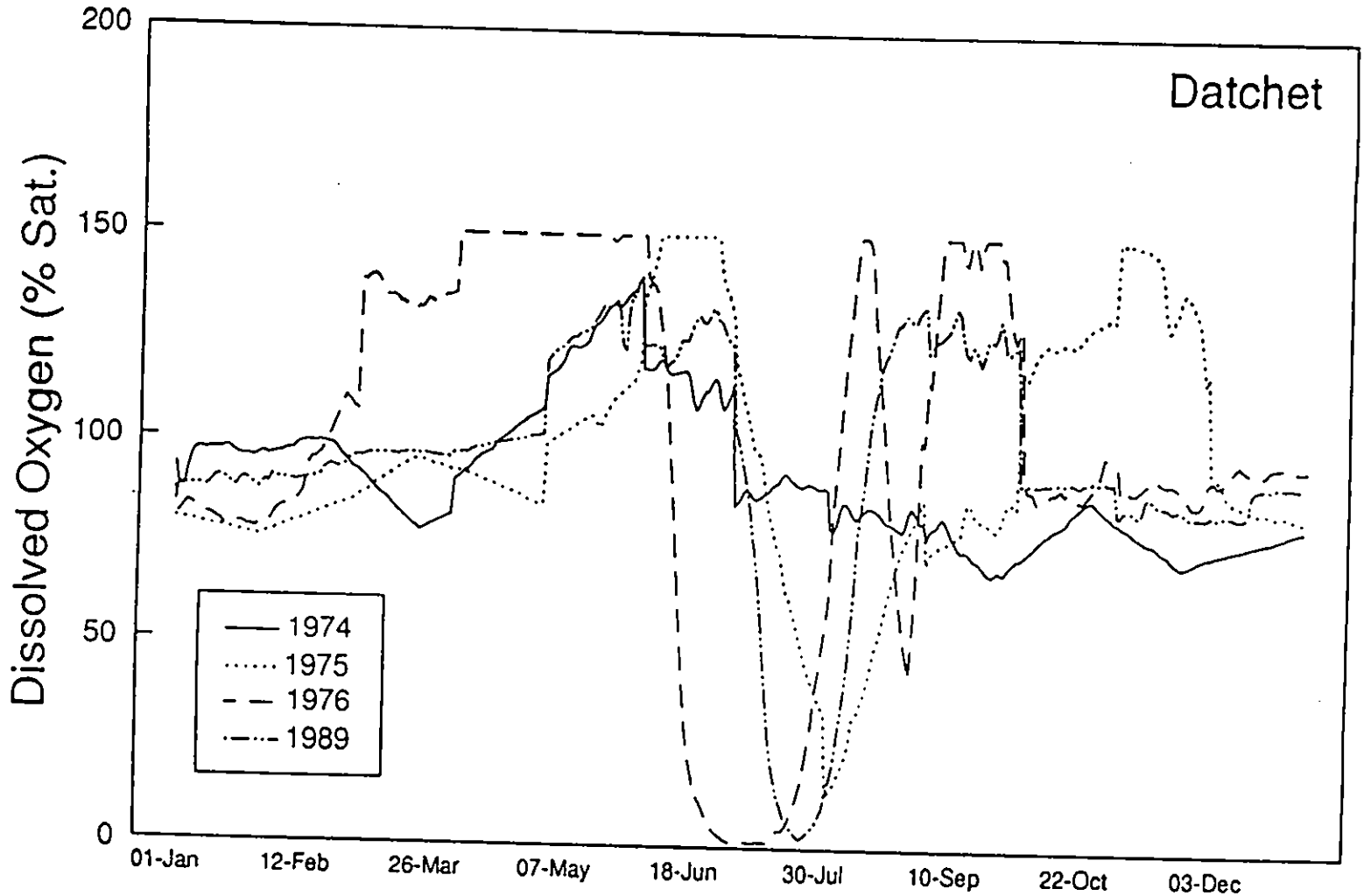


Figure 4.3a. Original dissolved oxygen (% saturation) at Datchet.

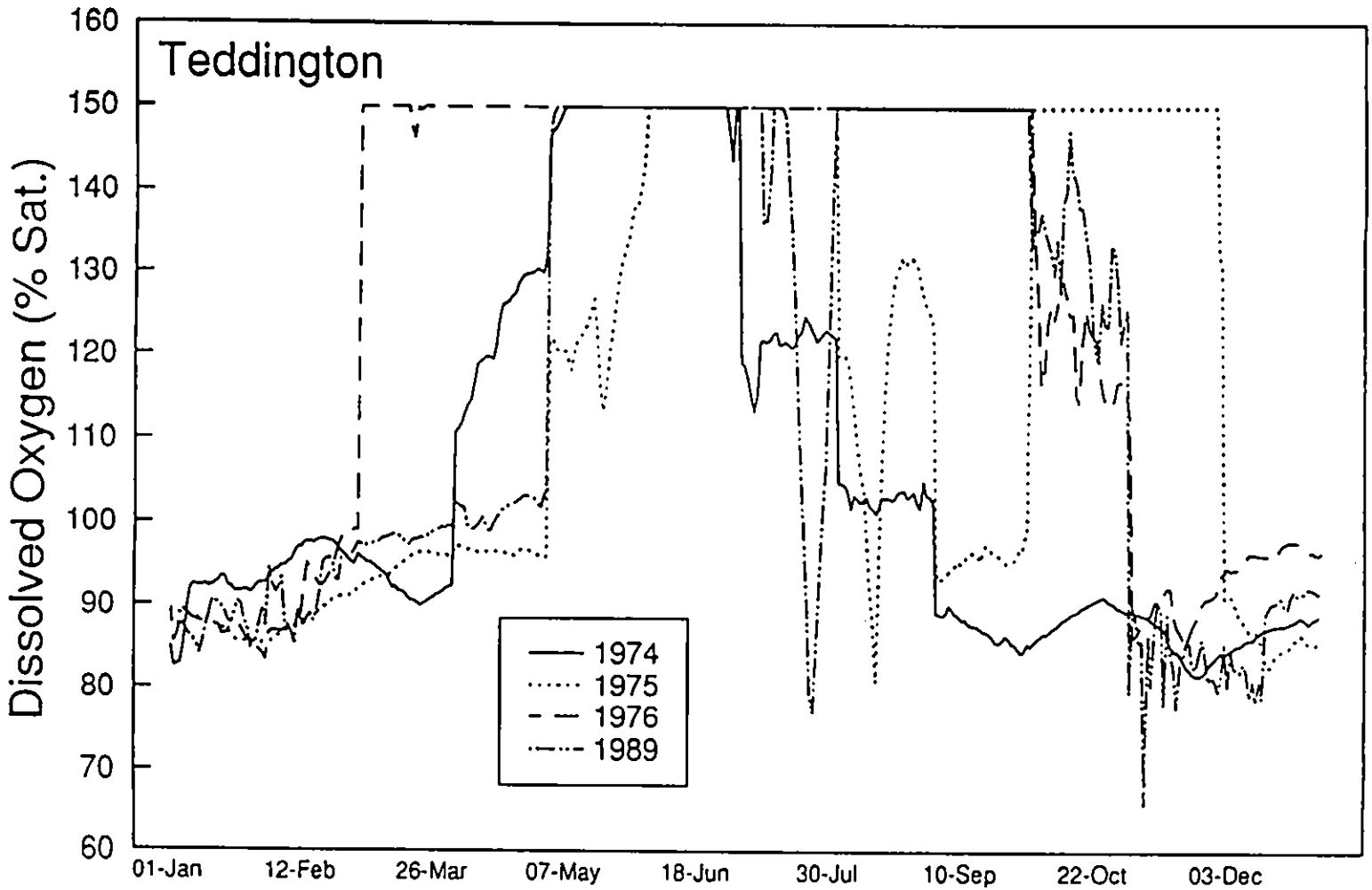


Figure 4.3b. Original dissolved oxygen (% saturation) at Teddington.

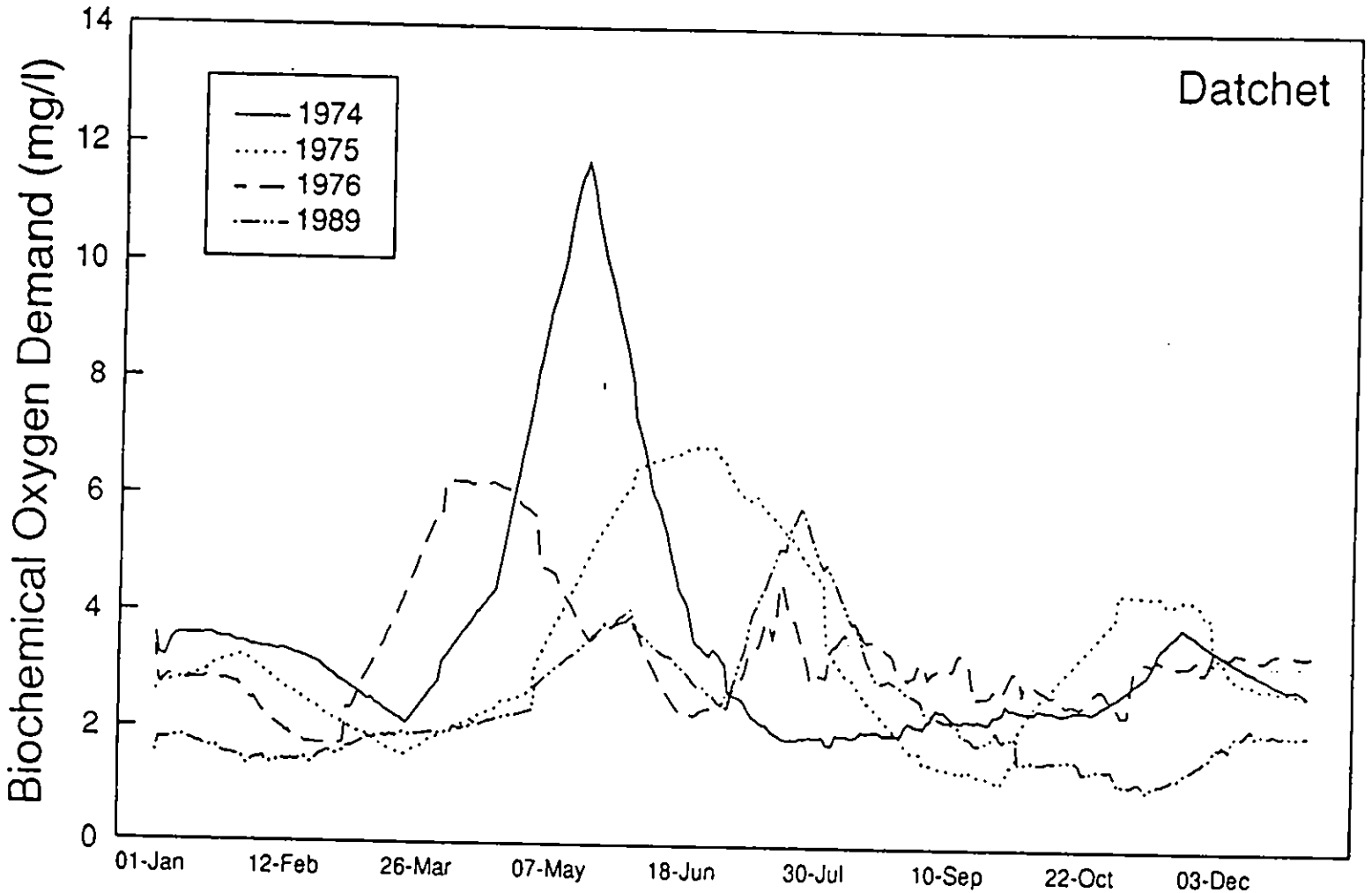


Figure 4.4a. Original biochemical oxygen demand (mg/l) at Datchet.

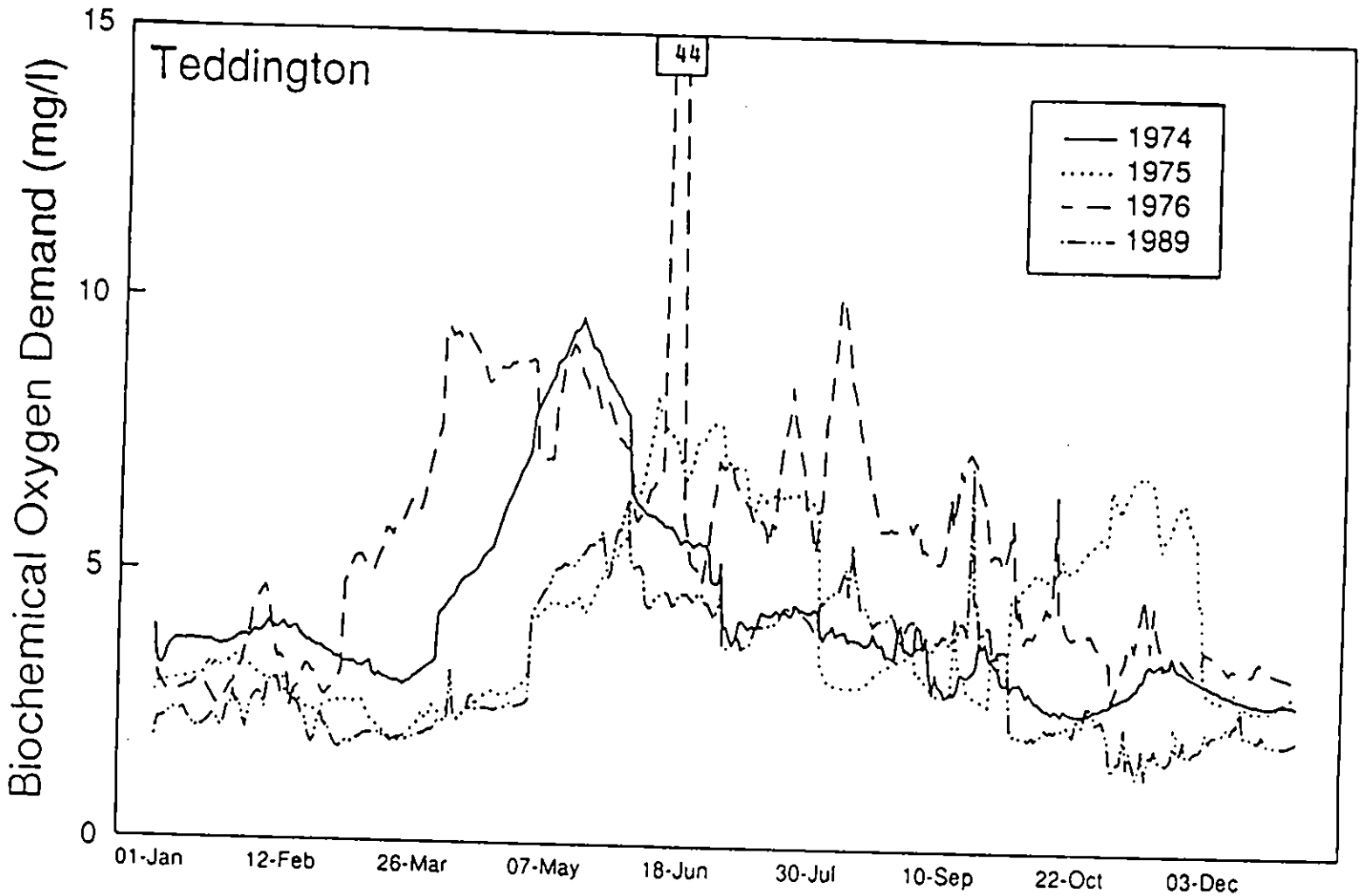


Figure 4.4b. Original biochemical oxygen demand (mg/l) at Teddington.

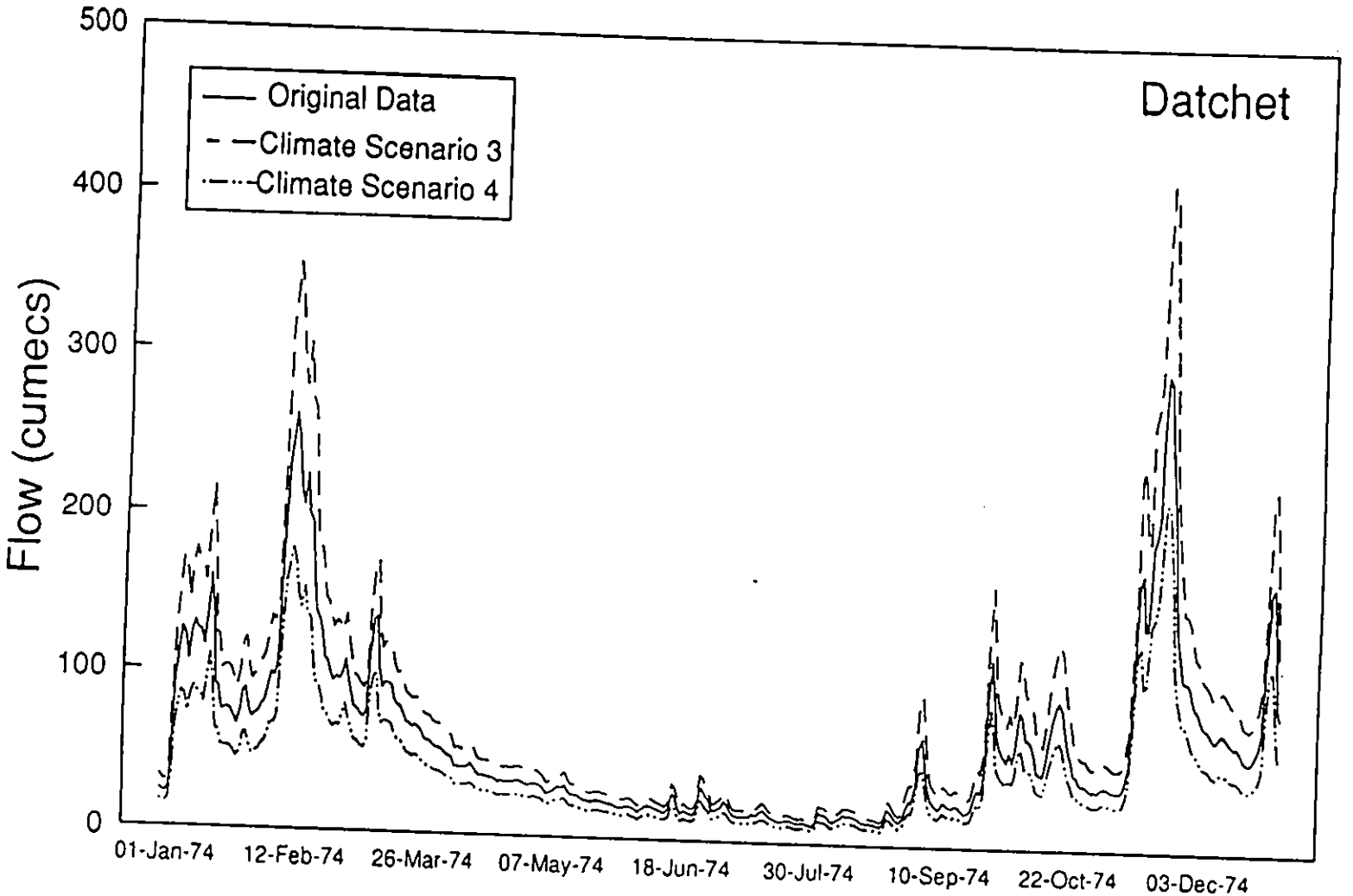


Figure 4.5. Original flow at Datchet during 1974 with adjustments due to extreme climate change scenarios shown.

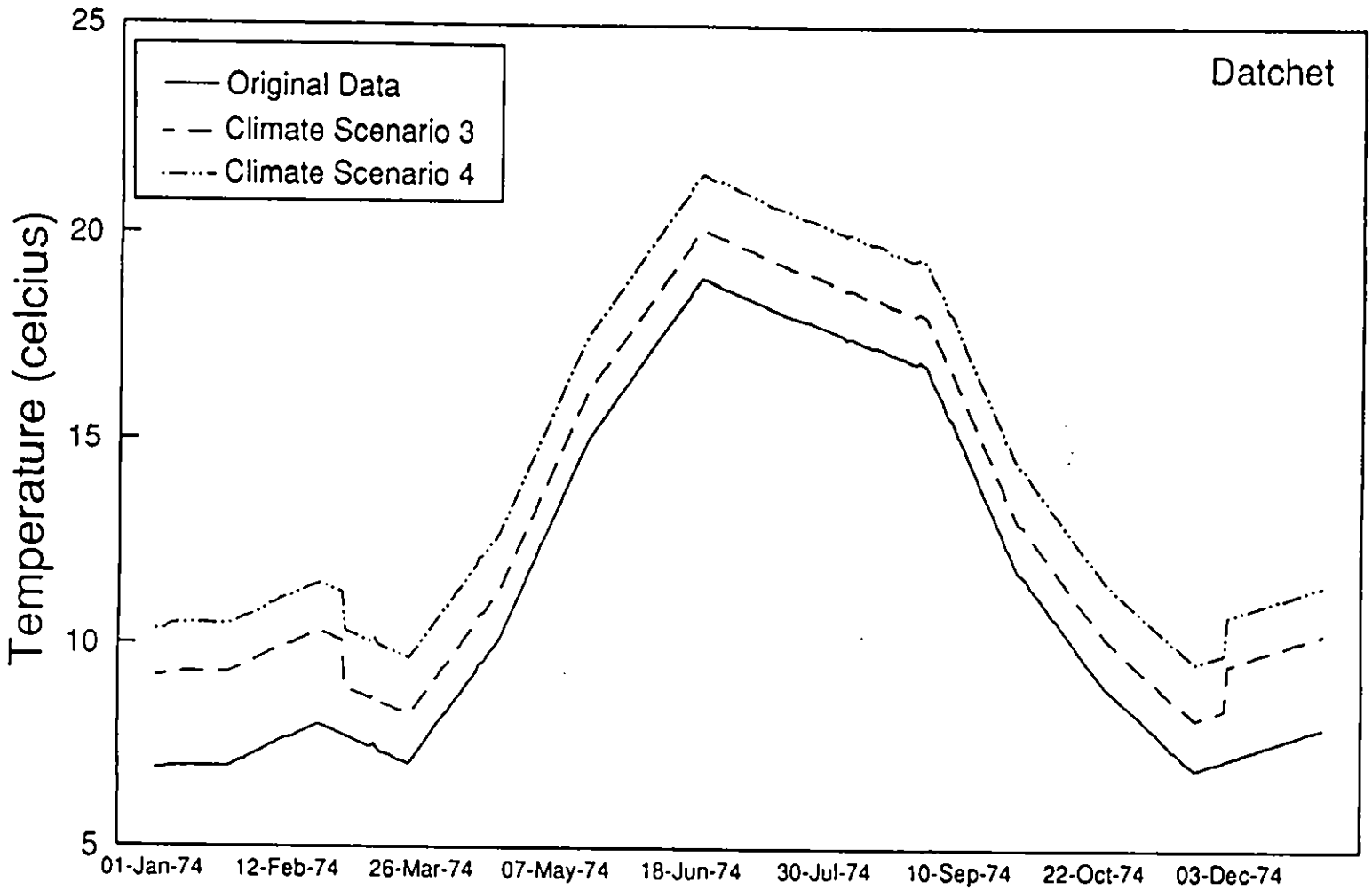


Figure 4.6. Original temperature at Datchet during 1974 with adjustments due to extreme climate change scenarios shown.

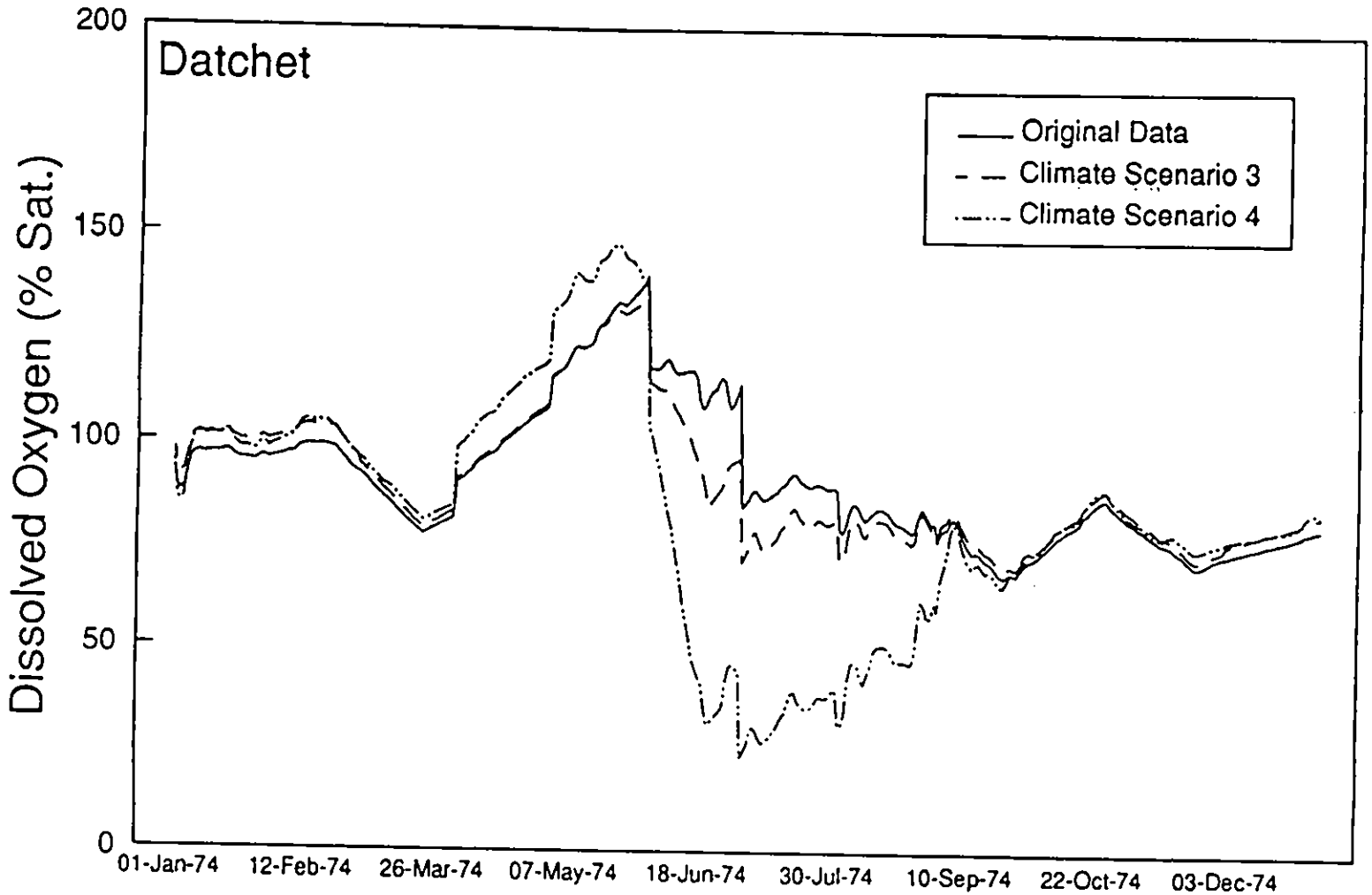


Figure 4.7a. Original dissolved oxygen (% saturation) at Datchet during 1974 compared to that under extreme climate change scenarios.

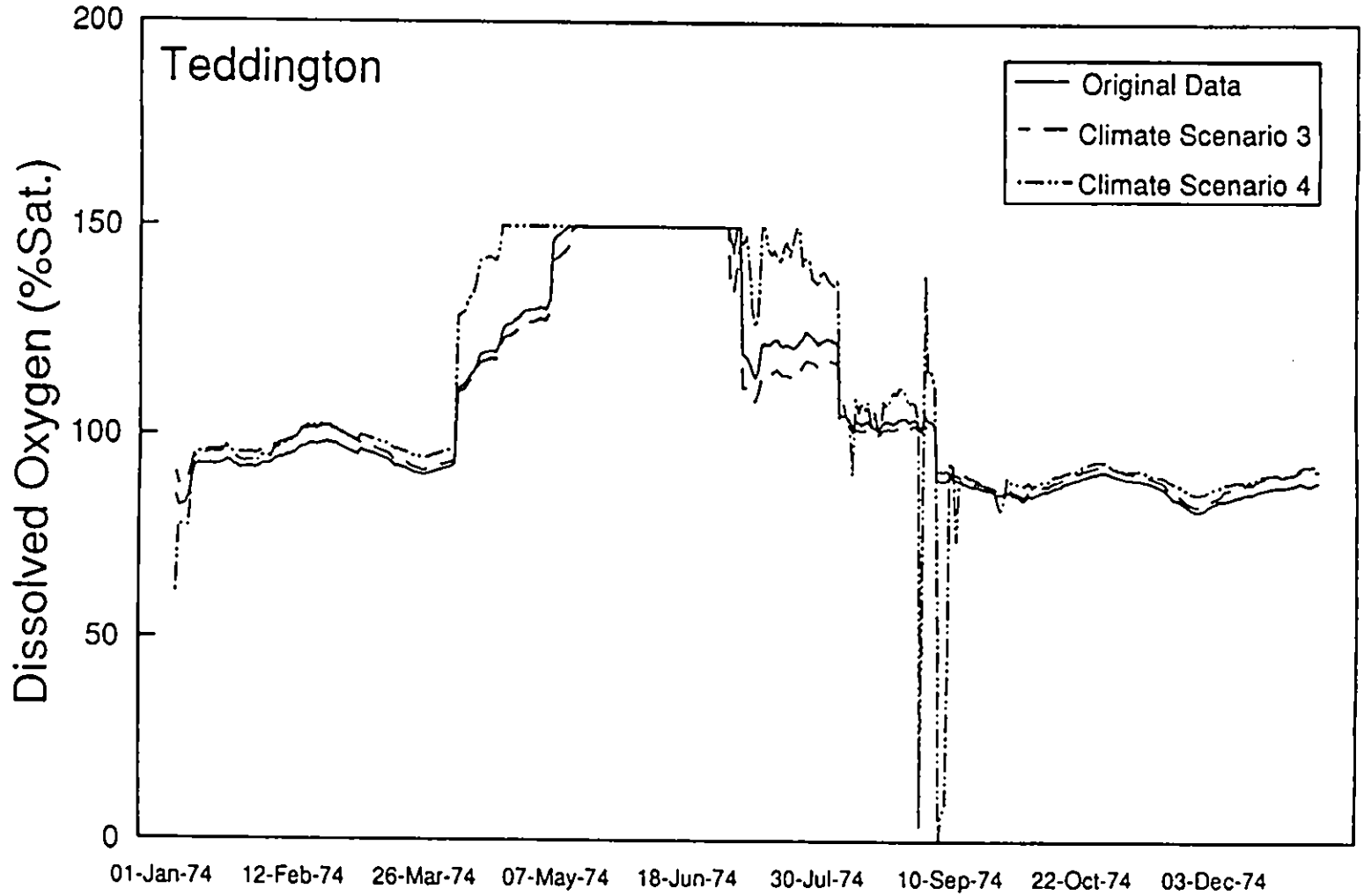


Figure 4.7b. Original dissolved oxygen (% saturation) at Teddington during 1974 compared to that under extreme climate change scenarios.

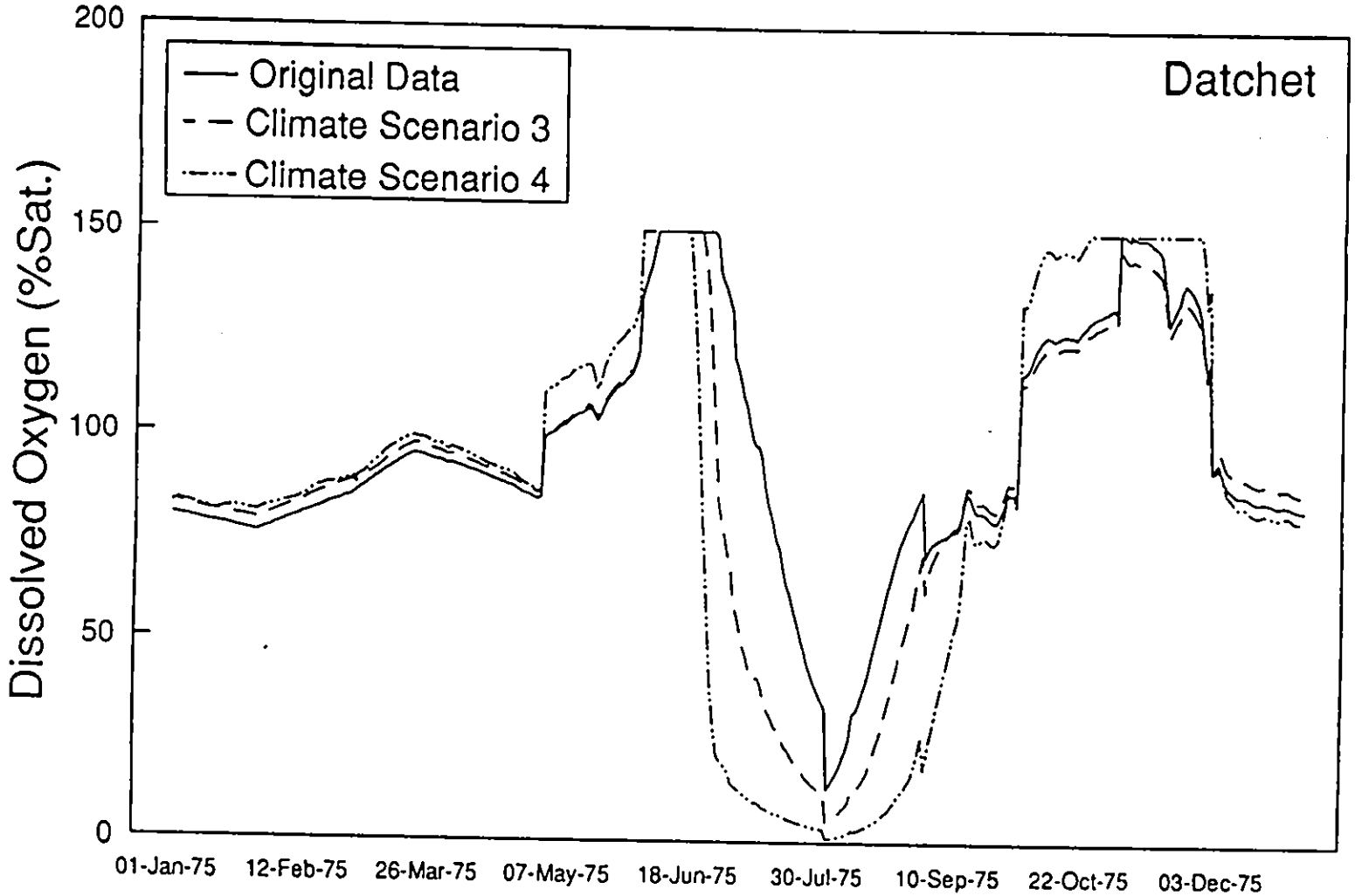


Figure 4.8a. Original dissolved oxygen (% saturation) at Datchet during 1975 compared to that under extreme climate change scenarios.

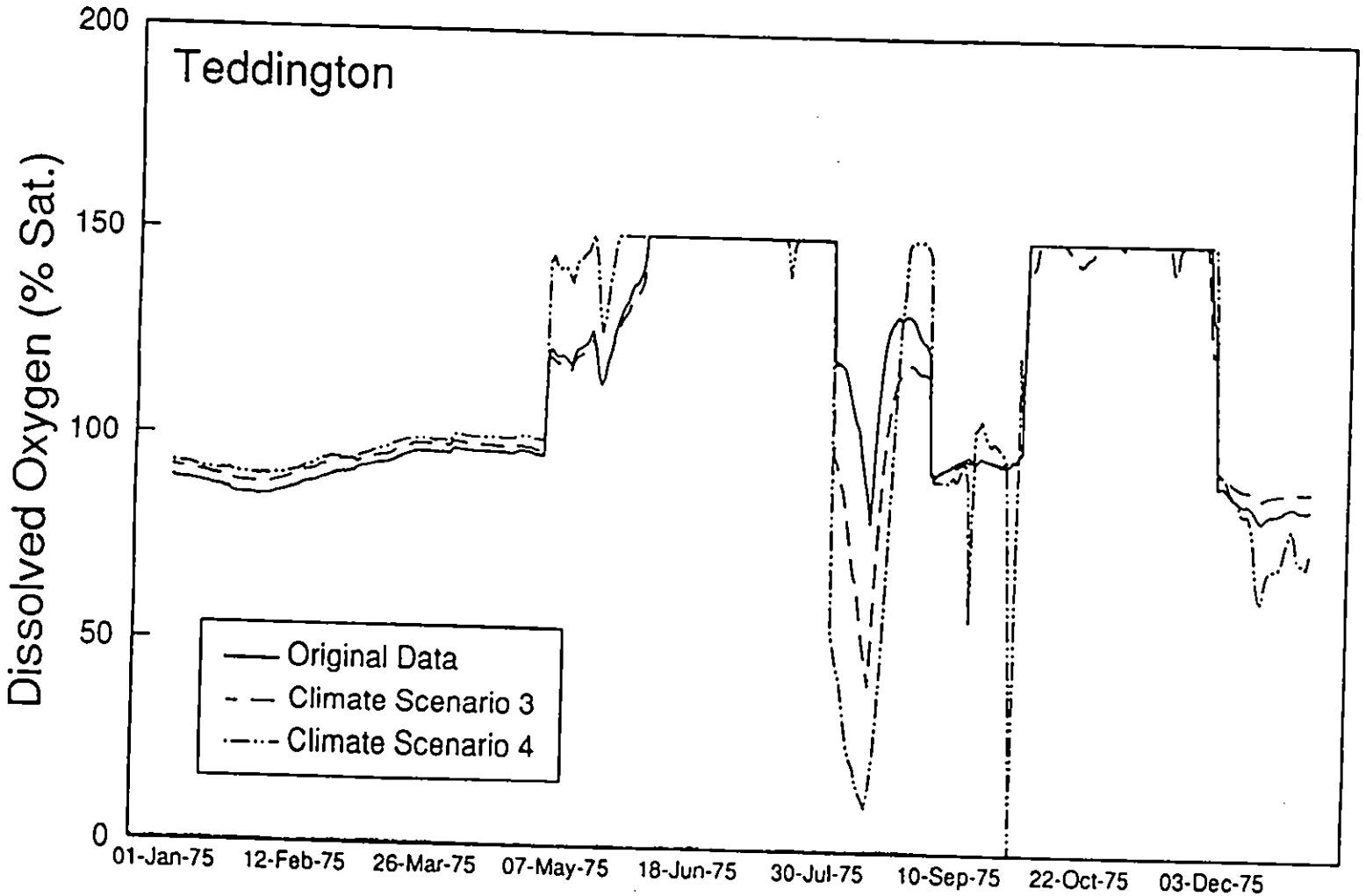


Figure 4.8b. Original dissolved oxygen (% saturation) at Teddington during 1975 compared to that under extreme climate change scenarios.

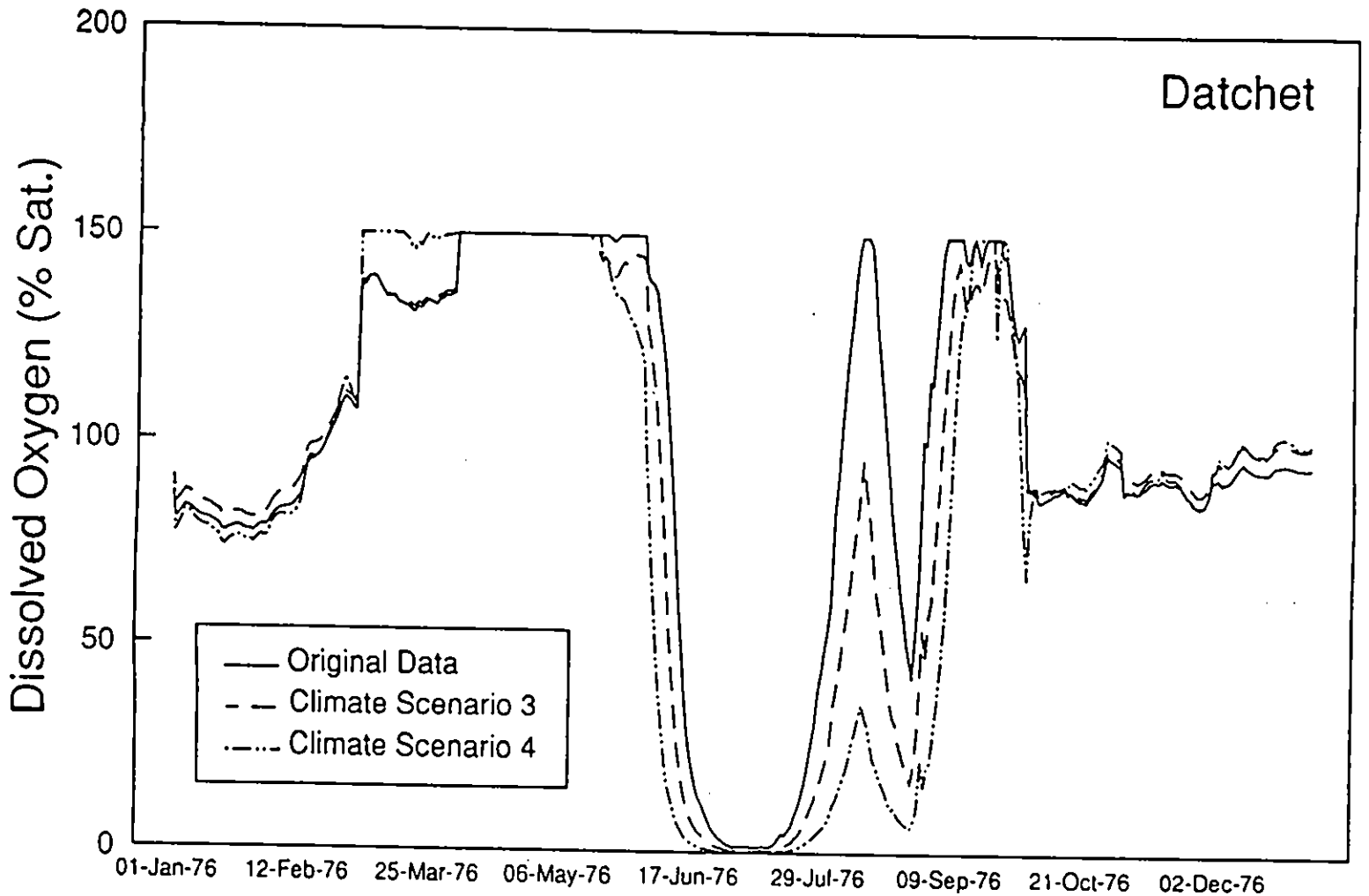


Figure 4.9a. Original dissolved oxygen (% saturation) at Datchet during 1976 compared to that under extreme climate change scenarios.

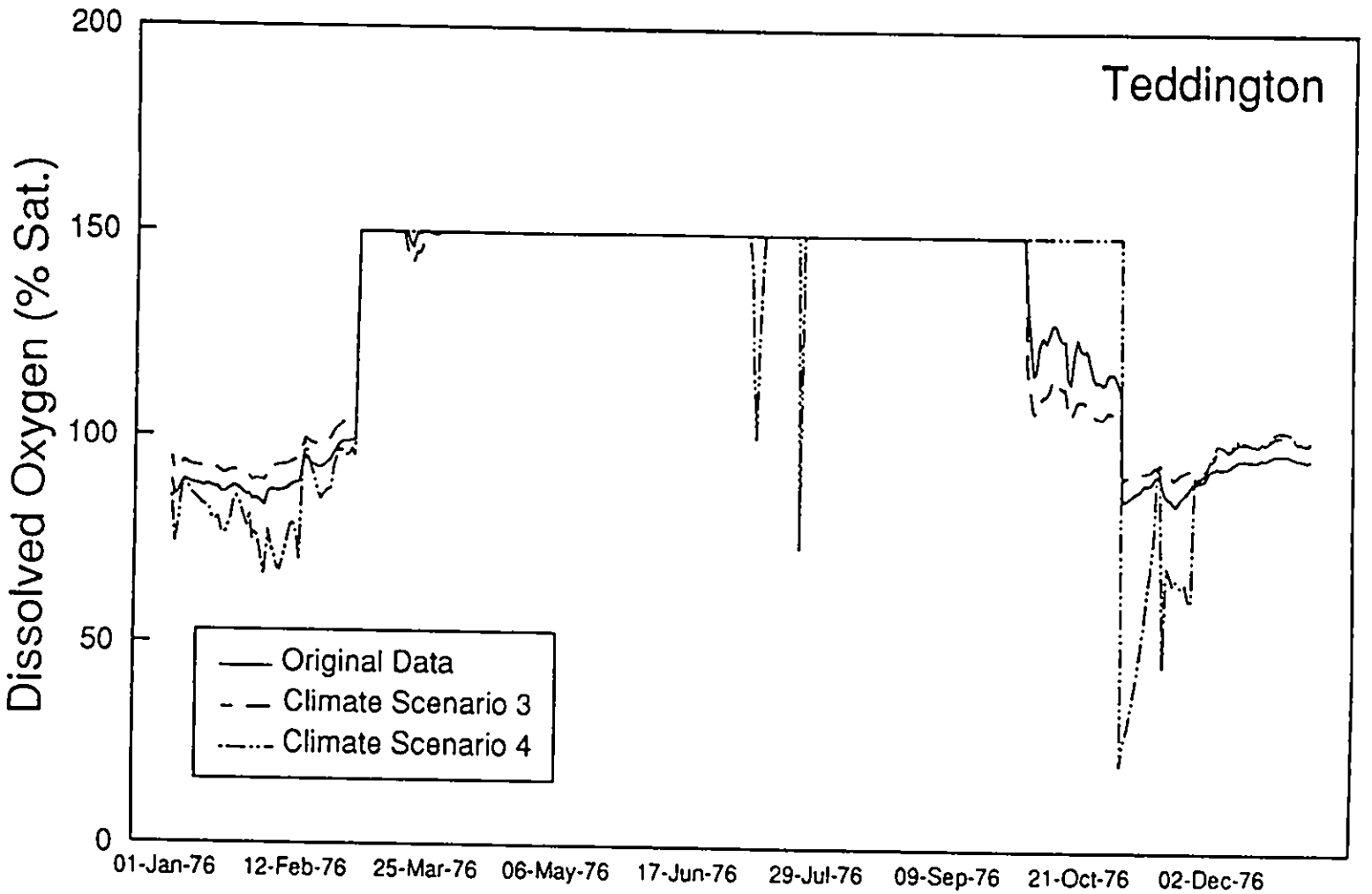


Figure 4.9b. Original dissolved oxygen (% saturation) at Teddington during 1976 compared to that under extreme climate change scenarios.

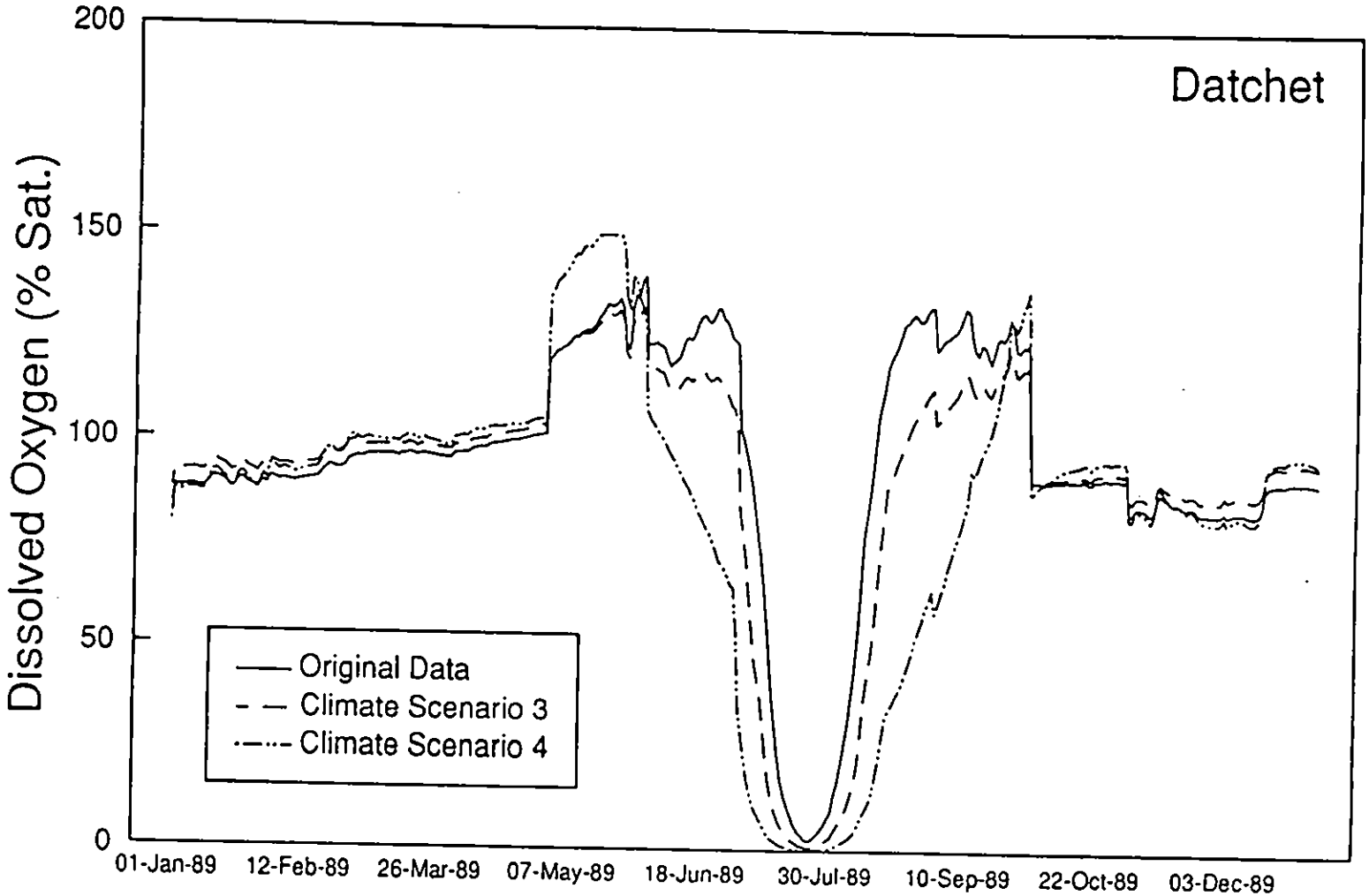


Figure 4.10a. Original dissolved oxygen (% saturation) at Datchet during 1989 compared to that under extreme climate change scenarios.

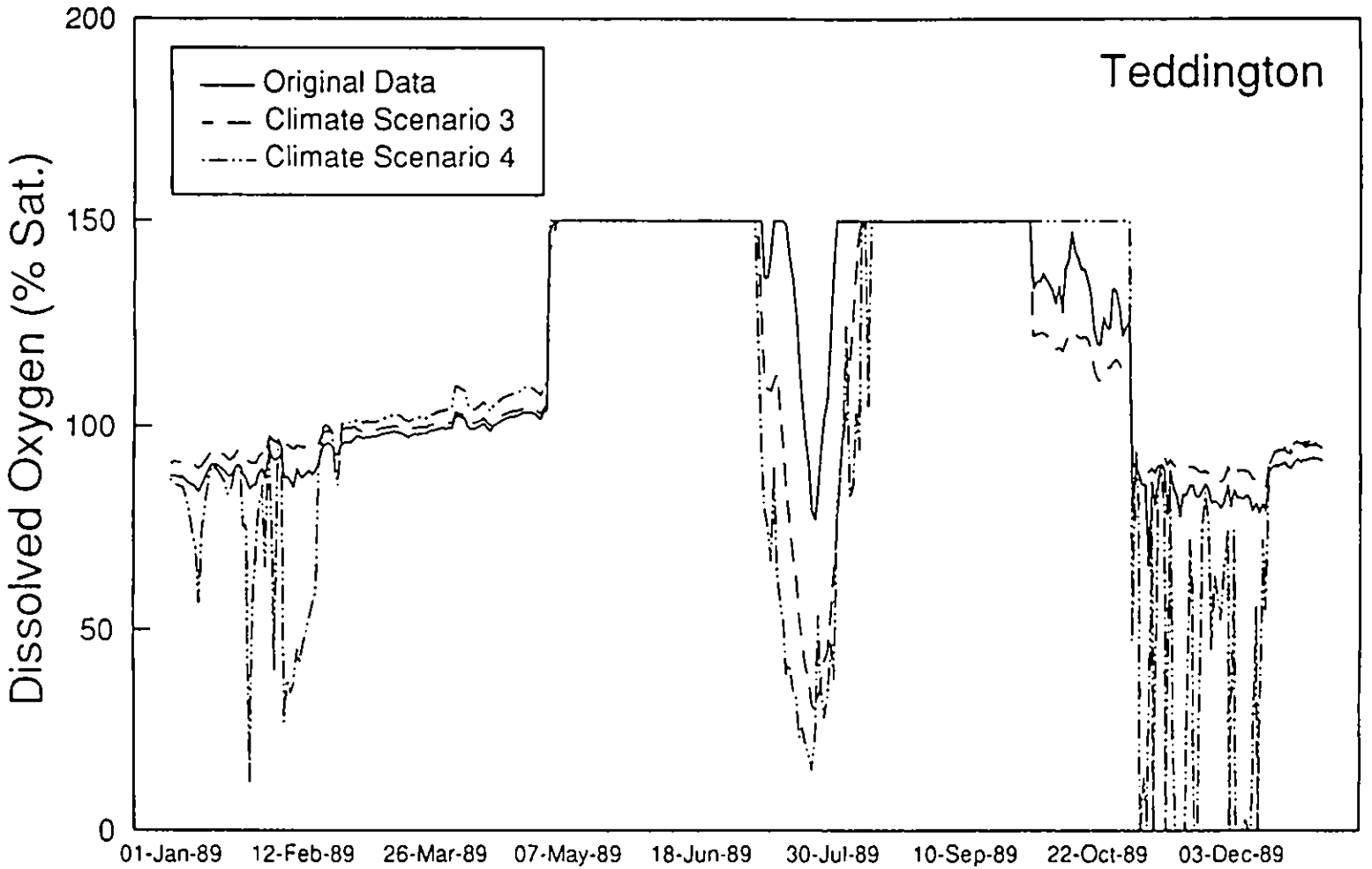


Figure 4.10b. Original dissolved oxygen (% saturation) at Teddington during 1989 compared to that under extreme climate change scenarios.

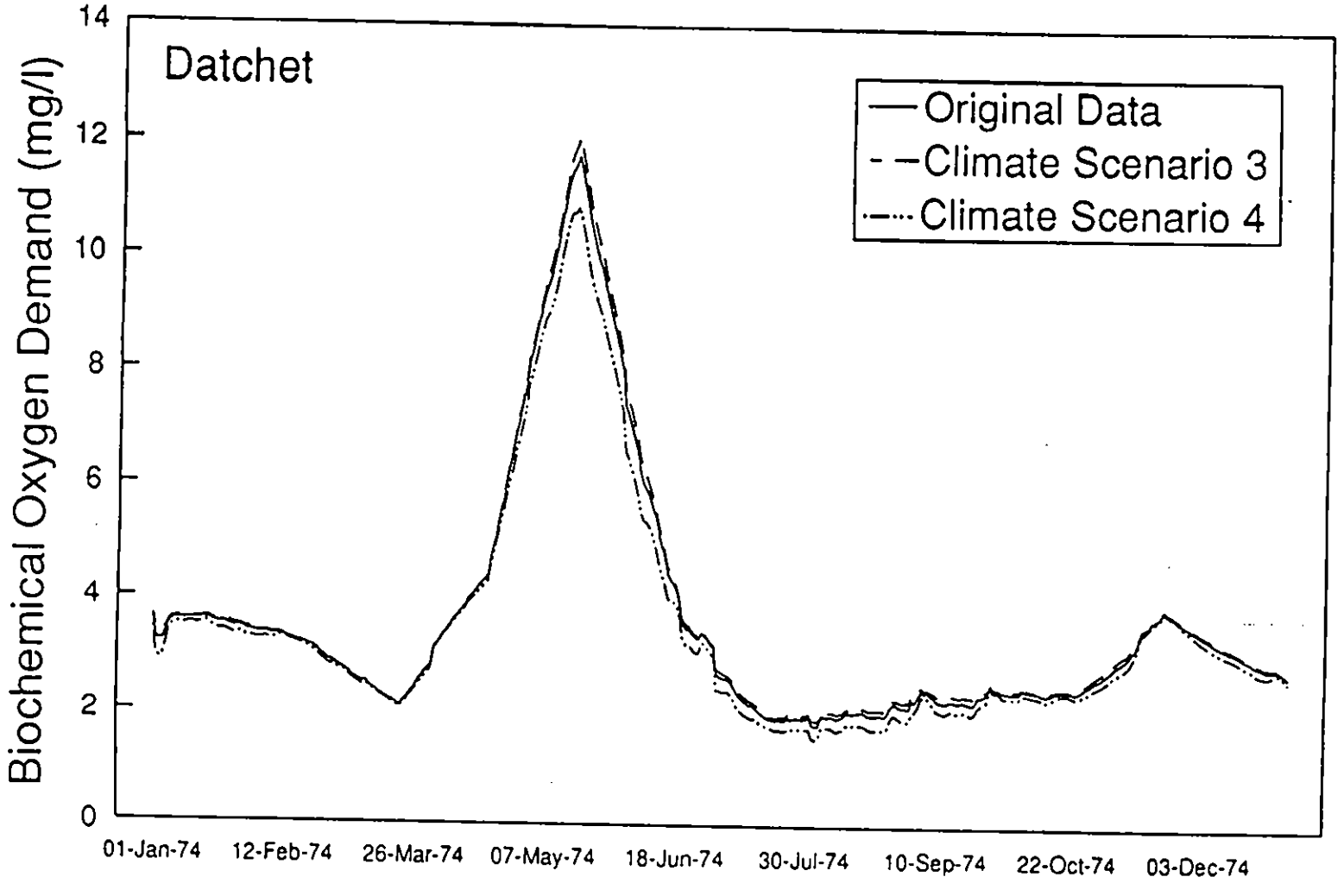


Figure 4.11a. Original biological oxygen demand at Datchet during 1974 compared to that under extreme climate change scenarios.

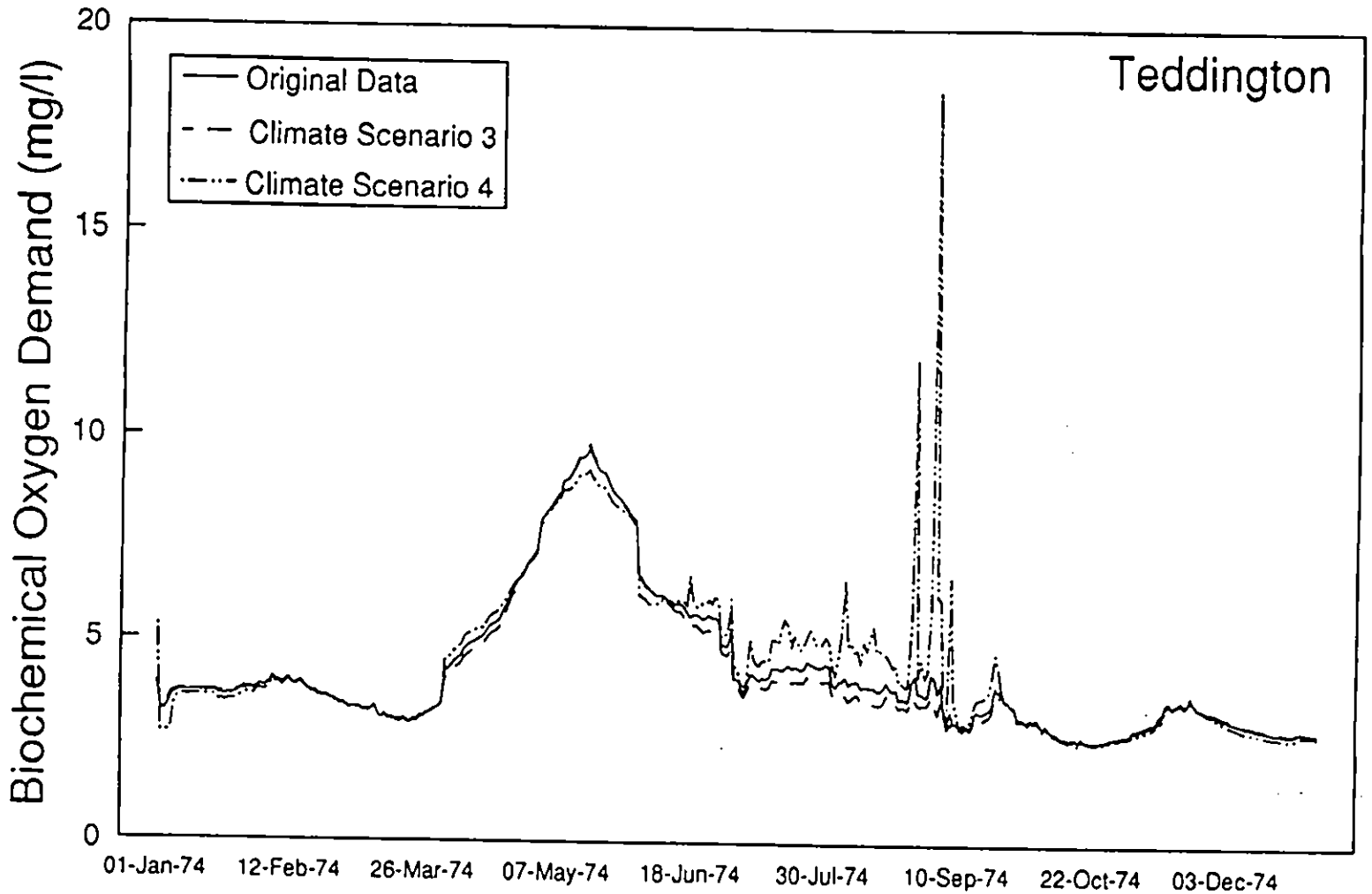


Figure 4.11b. Original biological oxygen demand at Teddington during 1974 compared to that under extreme climate change scenarios.

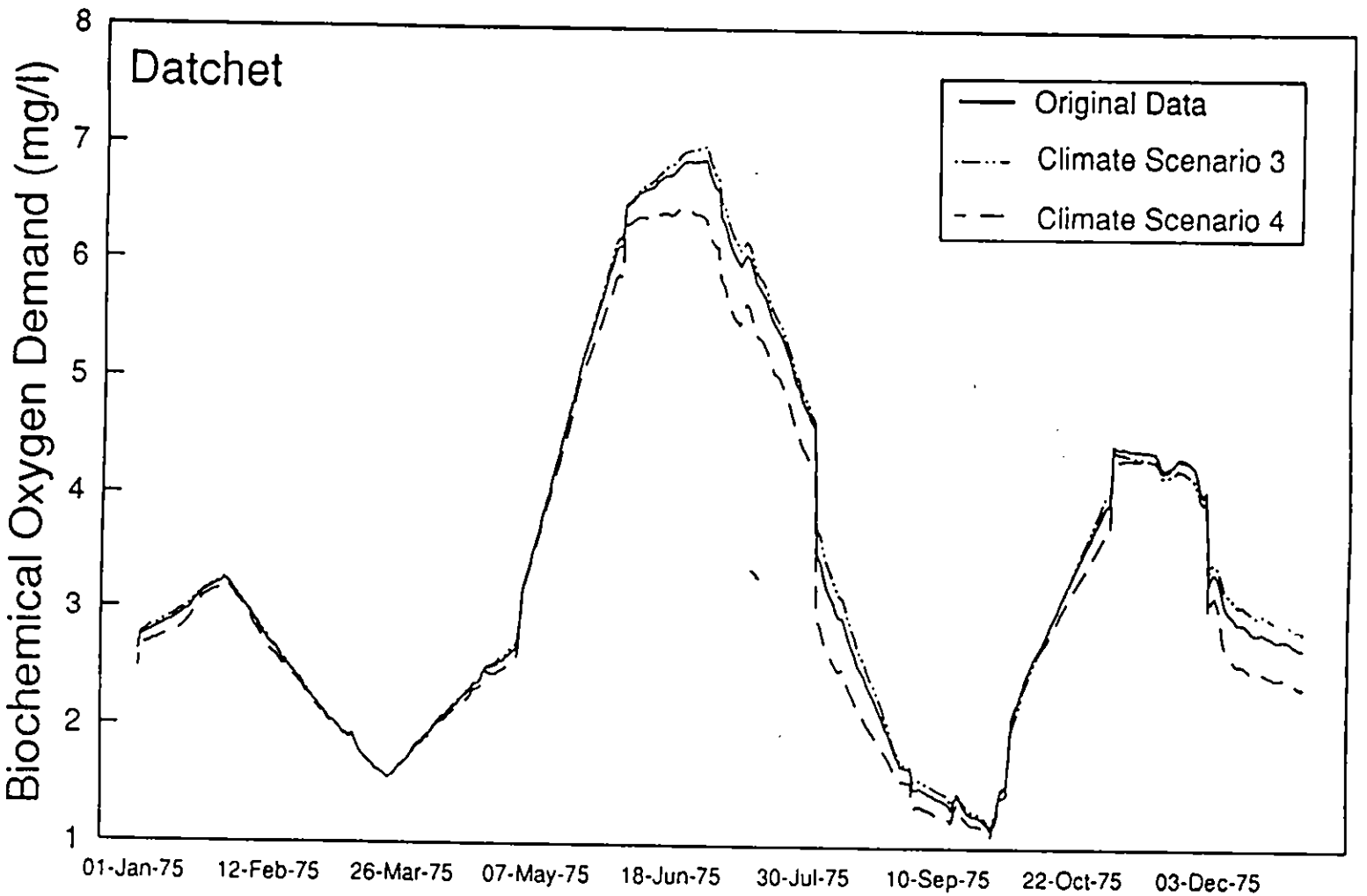


Figure 4.12a. Original biological oxygen demand at Datchet during 1975 compared to that under extreme climate change scenarios.

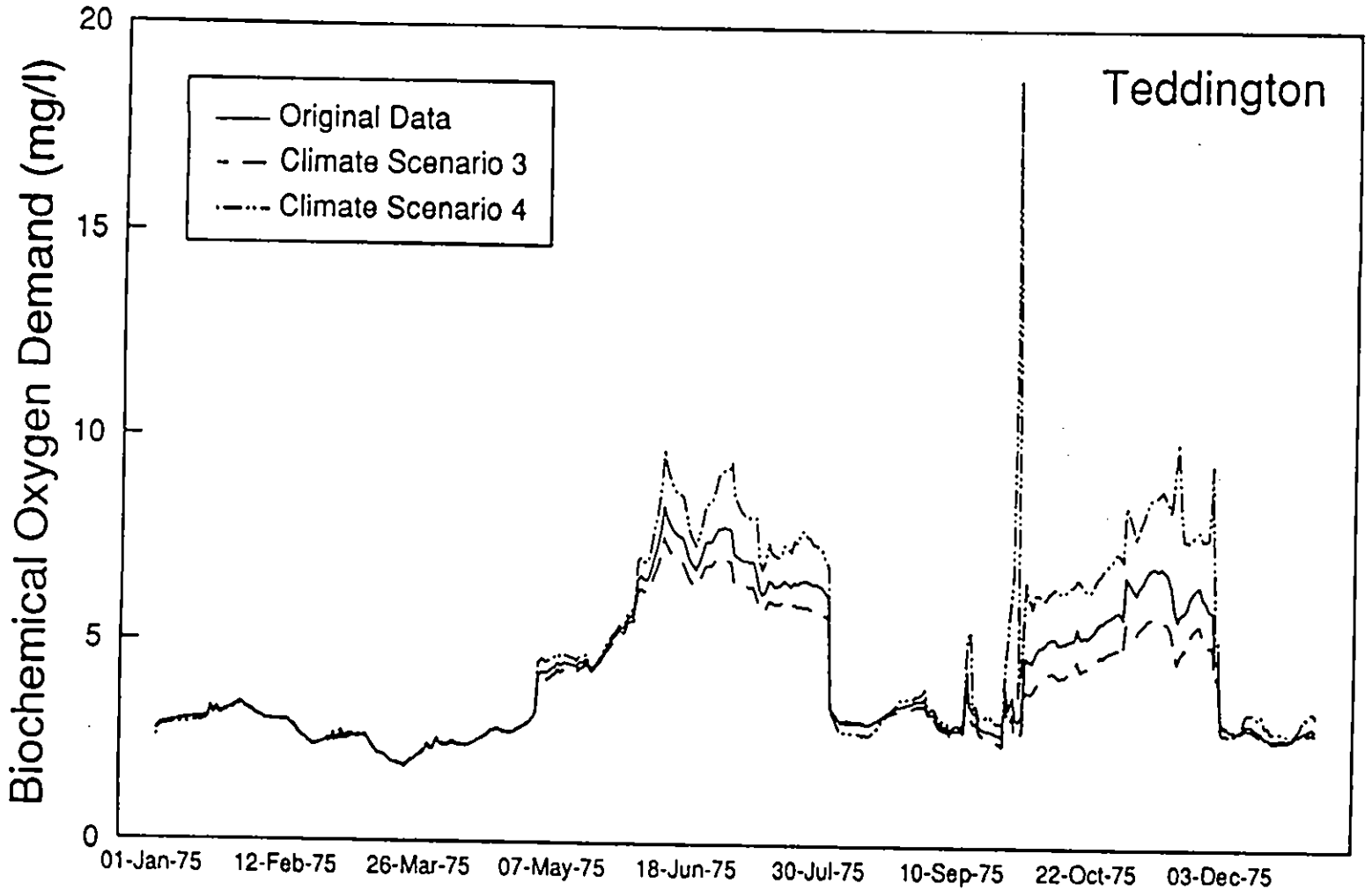


Figure 4.12b. Original biological oxygen demand at Teddington during 1975 compared to that under extreme climate change scenarios.

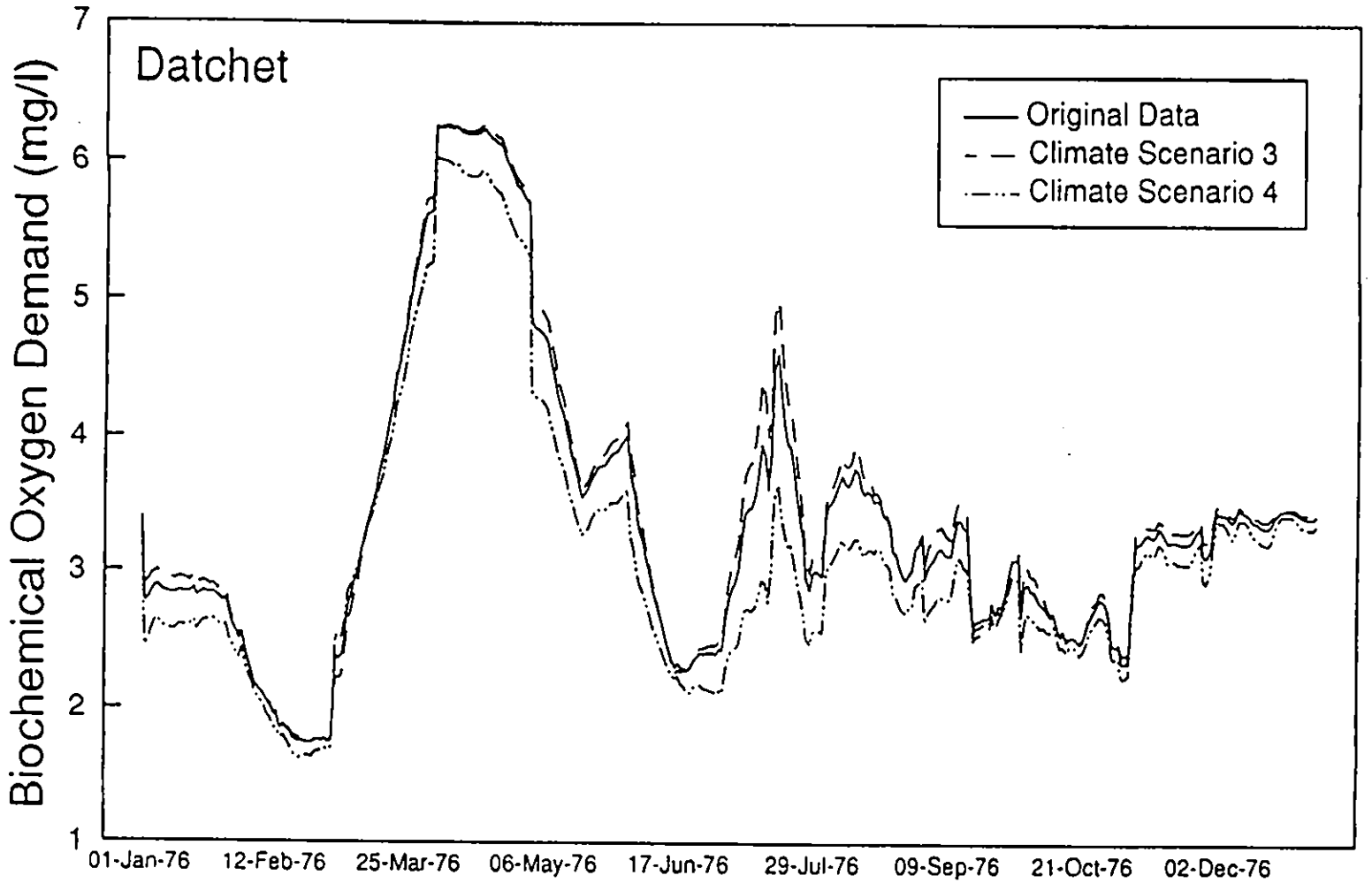


Figure 4.13a. Original biological oxygen demand at Datchet during 1976 compared to that under extreme climate change scenarios.

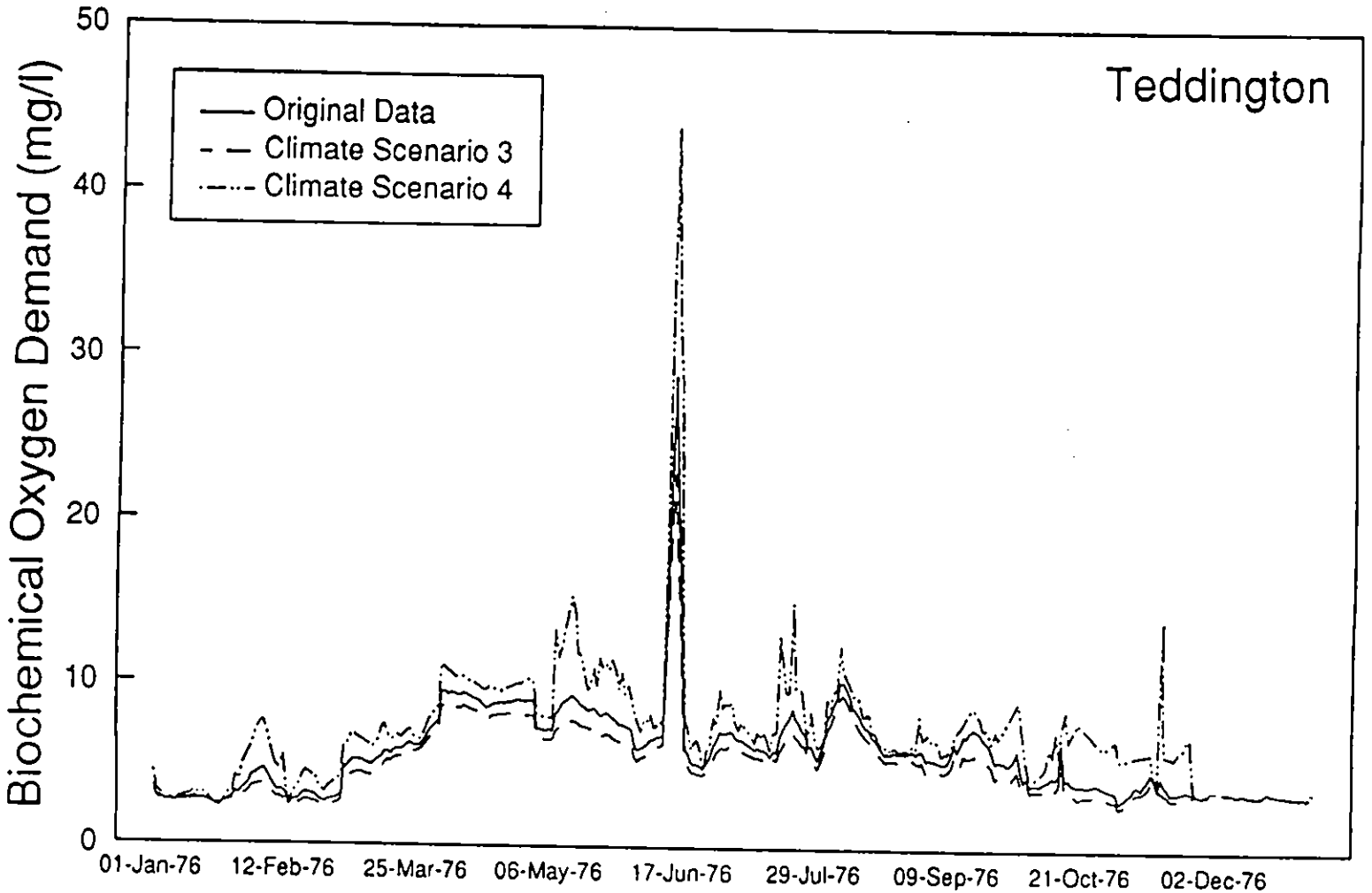


Figure 4.13b. Original biological oxygen demand at Teddington during 1976 compared to that under extreme climate change scenarios.

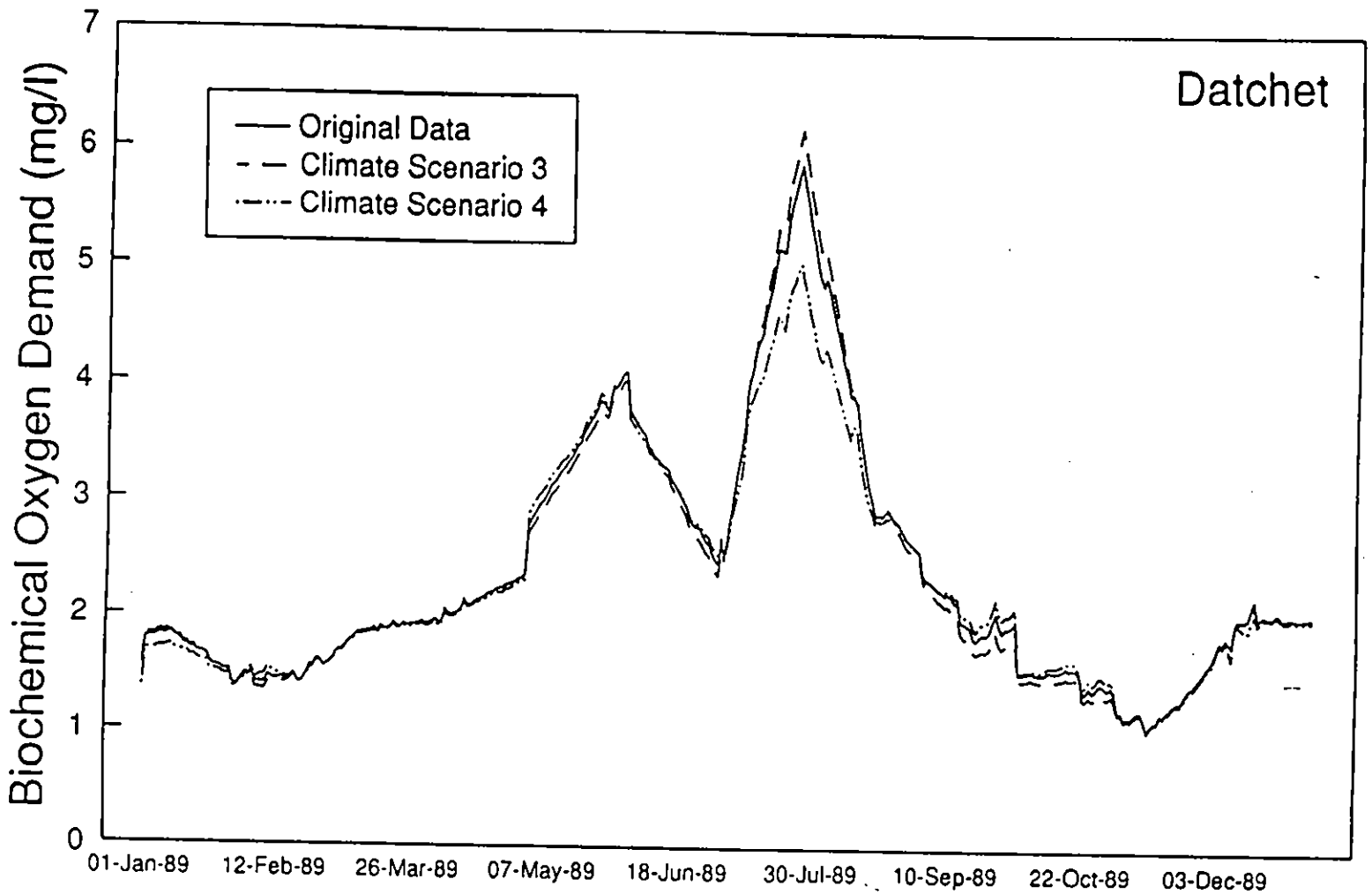


Figure 4.14a. Original biological oxygen demand at Datchet during 1989 compared to that under extreme climate change scenarios.

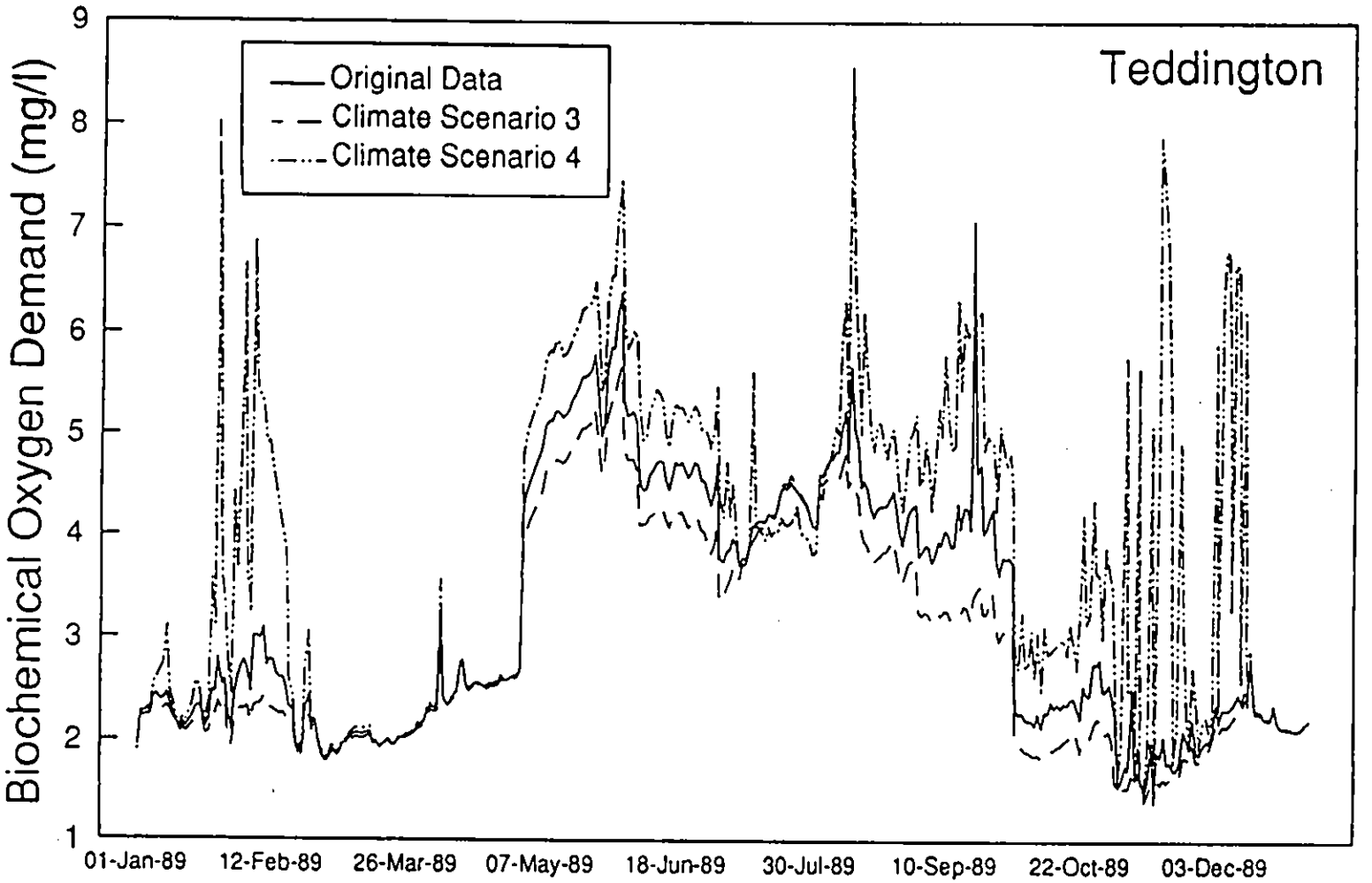


Figure 4.14b. Original biological oxygen demand at Teddington during 1989 compared to that under extreme climate change scenarios.

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APPENDICES.

APPENDIX A:
Equations solved by QUASAR.

APPENDIX B:
Explanation of the map files.

APPENDIX C:
Tables of results for climate change scenarios.

APPENDIX A

EQUATIONS SOLVED BY QUASAR

This appendix is divided into three sections. Because all the differential equations have essentially the same core, this core is given under Section 1. Section 2 gives the small changes relating to the water quality determinants, while Section 3 gives a detailed account of the underlying processes.

SECTION 1: Derivation of the main equation:

Flow will be considered as a simple derivation. For a reach volume V and length of reach l provided that we are dealing with the continuous case, then:

$$\frac{dV}{dt} = U - X$$

$$V = TC.Q$$

$$TC = \frac{1}{v.N}$$

where N is the number of lags (divisions within the reach), TC is the time taken for the water to travel down the reach with average velocity v, Q is the flow averaged over the length of the reach and the time step, U is the input flow to the reach and X is the output flow. Then, if we assume that the reach is a stirred tank system (which this model does assume) we know

$$X = Q$$

We also have the empirical relationship:

$$v = a + b.Q^c$$

where a, b and c are constants for each reach. Almost always a is zero, and in this case it is assumed to be zero. So: (by the chain rule)

$$\frac{dV}{dt} = \frac{d(TC.Q)}{dt} = Q.\frac{dTC}{dt} + TC.\frac{dQ}{dt}$$

But:

$$\frac{dTC}{dt}=\frac{d\left[\frac{1}{(v.N)}\right]}{dt}=-\frac{1}{N.v^2}.\frac{dv}{dt}=-\frac{TC}{NbQ^c}.b.\frac{dQ^c}{dt}=\frac{-TC.c}{N.Q}.\frac{dQ}{dt}$$

cancels out

So:

$$\frac{dV}{dt}=TC\frac{dQ}{dt}-\frac{c.TC}{N}\frac{dQ}{dt}=\left[1-\frac{c}{N}\right]TC\frac{dQ}{dt}=U-X$$

Independently of the no. of lags

Looking at the simpler case of only one lag, we have two cases:

(i) If c = 1 then U = X

(ii) If c in not 1, then

$$\frac{dX}{dt}=\frac{U-X}{(1-c)TC}$$

as X = Q (stirred tank).

The physical reason for the two different solutions is that the c = 1 case corresponds with the linear velocity-flow relationship. For the velocity to be proportional to the flow implies that the depth remains constant at all times. It is very rare for this condition to be satisfied by an unregulated river. However, for the Thames (being a regulated river) this linear velocity-flow relationship holds true.

SECTION 2: General equations:

In the same way equations may be derived for the other determinants.

It must be noted that when dissolved oxygen levels go to zero, the K_{15}, K_5 and K_1 terms are left out (which is equivalent to setting these constants to zero) in all equations.

-If c is not equal to 1 then we have:

Flow:

$$\frac{dX_1}{dt} = \frac{U_1 - X_1}{(1-c).TC}$$

where X_1 is the output flow and U_1 is the input flow (listed as X and U in the derivation for clarity).

Ammonia:

$$\frac{dX_6}{dt} = \frac{U_6 - X_6}{(1-c)TC} - K_{15}.X_6$$

where X_6 is the output ammonia concentration, U_6 the upstream ammonia concentration and K_{15} the ammonia nitrification rate.

Nitrate:

$$\frac{dX_2}{dt} = \frac{U_2 - X_2}{(1-c)TC} - K_{15}.X_6$$

where X_2 is the output nitrate concentration, U_2 is the upstream nitrate and K_5 is the denitrification rate.

Temperature:

$$\frac{dX_3}{dt} = \frac{U_3 - X_3}{(1-c)TC}$$

where X_3 is the output temperature (or concentration of conservative or hydrogen ions if these parameters are to be modelled), and U_3 is the corresponding upstream temperature.

Biochemical Oxygen Demand:

$$\frac{dX_5}{dt}=\frac{U_5-X_5}{(1-c)TC}-K_1.X_5-K_{18}.X_5+K_{10}$$

where X_5 and U_5 are the BOD concentrations, K_1 is the BOD decay rate, K_{18} is the sedimentation rate and K_{10} is the BOD contribution by algae.

Dissolved Oxygen:

$$\frac{dX_4}{dt}=\frac{U_4-X_4+WEIR}{(1-c)TC}+K_{11}-K_4.K_6.X_4+K_2(CS-X_4)-4.43.K_{15}.X_6-K_1.X_5$$

where X_4 and U_4 are dissolved oxygen concentrations, K_{11} is the net algae contribution, K_4 is the rate of sediment oxygen uptake while K_6 is a term depending on temperature and depth combining to give the benthic oxygen demand, K_2 is the reaeration rate with CS being the saturation concentration. WEIR is the contribution to the dissolved oxygen from any weirs in the reach (which is considered separately from the mass balance performed at an earlier stage).

Ortho-phosphate:

$$\frac{dX_8}{dt}=\frac{U_8-X_8}{(1-c)TC}-K_{16}.X_8$$

where X_8 and U_8 are the ortho-phosphate concentrations and K_{16} is the decay rate.

-If c is equal to 1 then we have:

Flow:

$$X_1=U_1$$

Ammonia:

$$X_6=U_6-K_{15}.X_6.TC$$

Nitrate:

$$X_2=U_2-K_5.X_2.TC+K_{15}.X_6.TC$$

Temperature etc:

$$X_3=U_3$$

Biochemical Oxygen Demand:

$$X_5 = U_5 - (K_1.X_5 + K_{18}.X_5 - K_{10})TC$$

Dissolved Oxygen:

$$X_4 = U_4 + WEIR + [K_{11} - K_4.K_6.X_4 + K_2(CS - X_4) - 4.43.K_{15}.X_6 - K_1.X_5]TC$$

Ortho-phosphate:

$$X_3 = U_3 - K_{16}.X_8.TC$$

SECTION 3: Processes in detail:

NITRATE PROCESSES:

Nitrification is the process resulting in the conversion of ammonium to nitrite and then to nitrate. The two biochemical reactions are shown below:

$$2NH_4^+ + 3H_2O \text{ - - (}\textit{Nitrosomonas}\text{ bacteria) - - -> } 2NO_2^- + 4H_3O^+$$

$$2NO2^- + O_2 \text{ - - (}\textit{Nitrobactor}\text{ bacteria) - - -> } NO_3^-$$

Curtis *et al.* (1974) studied nitrification in rivers in the Trent basin and found growth rates for *Nitrosomonas* and *Nitrobactor* were virtually the same. Laboratory work by Alexander (1965) showed *Nitrobactor* was five times as efficient as *Nitrosomonas* in doing its job. This indicates that ammonia (ammonium ion) concentration is the rate controlling process. Knowles and Wakeford (1978) modelled the change in nitrate concentration to be dependent on the ammonia and *Nitrosomonas* concentration and the temperature. In QUASAR the rate of change of nitrate concentration is dependent on the concentration of ammonia, the temperature and the ammonia nitrification rate, K_{15}, which is usually in the range of 0.01 to 0.5 days^{-1}. The value for the ammonia nitrification rate can be edited by the user. The equation is given below where T is the temperature in Celsius and K_{15} is the nitrification rate in days^{-1}.

$$Nitrification = K_{15}.10^{(0.0293T)}.X_6$$

Denitrification involves the reduction of nitrate to nitrogen gas and oxygen by denitrifying bacteria. The simplified reaction is given below:

$$2NO_3^- \text{ - - (denitrifying bacteria) - - -> } 3O_2 + N_{2(g)}$$

The oxygen produced is consumed by the bacteria as an oxygen source so does not add to the oxygen in the river. Toms *et al.* (1975) studied the factors affecting the denitrification process. These researchers found that the process is first order and proportional to the nitrate concentration, and required the presence of mud. They also found that for every 10°C increase in temperature the rate of denitrification increased by a factor of 1.9 which can be described in the equation as $10^{(0.0293T)}$. The relationship they developed is:

$$\frac{dNO_3^-}{dt} = -KA.CN.10^{(0.0293T+0.0294)}$$

where A(m^2) is the surface area of the mud in contact with the water, CN is the concentration of nitrate in contact with the water in mg/l and T is the average temperature in Celsius. K is a value in the range of 0.29 (clean gravel type bed), to 3.0 (soft muddy bed supporting denitrifying bacteria). In QUASAR modelling of denitrification is based on this work, but the constants are put together giving:

$$Denitrification = K_5.1.0698.10^{(0.02937)}X_2$$

Note that $1.0698 = 10^{0.0294}$. K_5 is in units of day^{-1} and in the range of 0.0 to 0.5 and can be edited by the user.

OXYGEN PROCESSES:

The contribution to or loss of dissolved oxygen due to the presence of a weir in a river is described by the equation (DOE 1973):

$$X_4 = CS - \frac{(CS - U_4)}{RT}$$

where CS is the oxygen saturation, U_4 is the upstream DO concentration and RT is the deficit ratio. This ratio takes into account the type of weir using a factor B, the pollution of the water (percent saturation) A, the height from the top of the weir to the downstream level H (m), and the temperature t (°C) of the water as shown below:

$$RT = 1 + 0.38A.B.H(1 - 0.11H)(1 + 0.46T)$$

There are 4 types of weirs; free, slope, step and cascade. A free or normal weir takes a B value of 1. A step weir has a B value of 1.3. A cascade weir consisting of a large number of steps has a B value of 0.4 and a sloping weir has a sloping face down and has a B value of 0.2.

Algae, aquatic plants and phytoplankton utilize water, carbon dioxide and sunlight to photosynthesize simple sugar and oxygen which is released to the water column. Respiration, which depletes the dissolved oxygen store in the water, occurs throughout the 24 hours. These two processes result in the highest dissolved oxygen concentration at mid afternoon and the lowest just before dawn. The two processes are described below and related in the differential equation by K_{11} = P - R where P is photosynthetic oxygen production and R is respiration.

Photosynthesis oxygen production in a river system has been described by Owens *et al.* (1969) in which oxygen production is related to the light intensity and plant biomass or algal levels. They found that once there is sufficient plant biomass to provide adequate and uniform cover of the river bed the plant biomass has apparently no effect on the rate of photosynthesis due to self-shading. Whitehead *et al.* (1981) used a modified version of the Owens model and estimated the relevant parameters for the Bedford Ouse. A similar approach was adopted for QUASAR and the following relationship developed:

Chlorophyll-a concentrations less than 50 mg/l:

$$P(mgl^{-1}day^{-1}) = K_8(1.08^{(t-20)}I^{0.79}0.317Cl\text{-}a)$$

Chlorophyll-a concentrations greater than 50 mg/l:

$$P(mgl^{-1}day-1)=1.08^{(t-20)}I^{0.79}(K_8(0.317x50)+K_9 0.317Cl-a)$$

Here the user specifies the two rates at which photosynthetic oxygen production occurs, one when the chlorophyll-a concentration is greater than 50 mg/l, K_8, and one when it is less than 50 mg/l, K_9. K_8 is usually in the range 0.0 to 0.3 day^{-1}, and K_9 is in the range of 0.0 to 0.02 day^{-1}. The two rates are to take account of the self shading effect at high algae concentrations. Cl-a is the chlorophyll-a concentration (gm^{-3}), I is the solar radiation level at the earth's surface (W hr m^{-2} day^{-1}) (= 1/24 J m^{-2} s^{-1}). I is only input during sunlight hours determined from longitude and latitude data and also from the time of year. This assumes no cloud cover.

Respiration of algae giving rise to loss of oxygen is described by an equation developed from Kowalczewski and Lack (1971) based on observed algae concentration measured as chlorophyll-a and respiration rate for the river Thames. Cl-a and T are as before.

$$R(mgl^{-1}day^{-1})=(0.14+0.013Cl-a)1.08^{(t-20)}$$

Oxygen is also lost by benthic oxygen demand (river bed or mud respiration). There has been considerable research into this process (Edwards & Rolley, 1965) and the following equation has been used, where M is the benthic oxygen demand:

$$M=\frac{1.08^{(T-20)}.K_4.X_4^{0.45}}{d}$$

where X_4 refers to the DO concentration (mg/l), d is the river depth in metres, K_4 is the rate of oxygen uptake by the sediment and T is the temperature in degrees Celsius. The original work of Edward and Rolley was conducted on the highly polluted mud of the river Ivel and later studies by Rolley and Owens (1967) showed that the parameter K_4 of 0.15 day^{-1} was found to provide the best fit to the observed DO data. K_4 is the oxygen uptake rate by sediment, usually in the range of 0.0 to 0.1 day^{-1}. This value can be edited by the user. d is the river depth in metres and is specified in the spacial data for the reach and T is the temperature in Celsius.

Oxygen is added to the system by the natural reaeration of the river at the surface. Several workers have developed empirically and physically based equations. Edwards & Gibbs combined previous work of Churchill *et al.* (1962) and Gameson (1955) to derive the equation:

$$Reaeration=K_2(CS-X_4)$$

where K_2 is given by

$$K_2=\frac{38.2V^{0.67}}{d^{1.85}}(day^{-1})$$

APPENDIX B

EXPLANATION OF THE MAP FILE

The map file 'describes' the river network and the reaches etc. within a river. Each river is described in its entirety before the next one is begun. The rivers are listed in 'run' order. The first record for a river describes the number of tributaries in the river and also the name of the river.

POINTS/TRIBUTARIES/RIVERS

These records describe each of the points or tributaries in each reach of the rivers of the network. The first record gives the name of the point/tributary and the river and reach into which if flows. Also included is the type of point: ABStraction, RIVeR, DISCharge, EFFLuent, TRIButary or NONE. The first character of the record is % to allow programs to check synchronisation while reading the map file. For example a point which flows into reach 6 of river 4 has the following record:

%006_004 TYPE Name of point/tributary

The next record defines the number of reaches, the number of indirect (additional) inputs to this point (such as Sewage Treatment Works). The format of this record is: (216).

If there are indirect discharges then the next records describe them. There is one set of records for each indirect discharge. The first record simply gives the name of the discharge. Following this are N_DET determinants. The first record of each set specifies the source of the data, this maybe followed by none, one or more records depending on the source. The determinants appear in the order:

Flow (cumecs)
Nitrate (mg/l)
Chloride (mg/l)
Dissolved Oxygen (mg/l)
Biochemical Oxygen Demand (mg/l)
Ammonia (mg/l)
Temperature (Celsius)
Ortho-phosphate
pH

The indirect discharges are then followed by N_DET sets of records for the point/tributary/river in the same order.

The first three characters of the first record are an integer code that indicate the source of the data, the forth character is left blank and the remainder of the record is specific to the source type if required. Access codes used are:

0 The value for this determinant is obtained elsewhere.

1 The data is obtained from a network outstation.

Current understanding is: Station name is a six character Mnemonic, determinants are six character Mnemonics. Values available from the VAX RDB are integer values which must be scaled, provide an offset and slope.

2 The data is obtained from the equation:

$$FLOW=EXP(A+B\text{x}\ln FLOW)$$

where A and B are constants returned from the remainder of the record. This equation can therefore not be used to find the flow determinant.

3 The data is obtained from the equation:

$$FLOW=EXP(A+B\text{x}FLOW)$$

where A and B are constants returned from the remainder of the record. This code can not, therefore, be used to find the flow determinant.

4 The data is the constants in the table of mean monthly values for this determinant.

5 The data is the constants in the table of mean daily values for this determinant.

REACHES

The river is split into one or more rivers. The first record of the river is the same as the point/tributary introduction record (they are basically the same thing anyway). A river may flow into another river. The type code for a river is RIVR and the name is (of course) the name of the river. The next records are the same as the above (and are for the river, not its reaches,which have their own special records).

The next record gives the bit array specification for the 32 bit mask which indicates which other rivers must be run to run this one. Each river has a 32 bit mask which says which of the other rivers flow into it (and therefore must be run to run that river). The rivers are numbered in order of distance up the network (i.e. the main river has the highest number, and the river that flows into it has a lower number, and any river that flows into that has an even lower number). The MSBit of the mask is in column one.

The records following this describe data relevant to the reaches. Each reach is listed in the order in which it appears in the river. The first of these records gives the reach 'name'. The reach name is usually in the form of "head - tail". The next record gives the reach length (m), the mean width (m), the mean depth (m), the time zone, the latitude and longitude. The next

record contains the number of lags and the flow - velocity relationship (three values). The next record contains the rate coefficients for the reach:

Denitrification rate	0.0 to 0.5
Biochemical oxygen demand decay rate	0.0 to 2.0
Ammonia nitrification rate	0.0 to 0.5
Rate of oxygen uptake by sediment	0.0 to 1.0
Rate of biochemical oxygen demand addition by dead algae	0.0 to 0.1
Rate of photosynthetic oxygen production for chlorophyll-a concentrations of 0.001-50 mg/l	0.0 to .03
Rate of photosynthetic oxygen production for chlorophyll-a concentrations above 50 mg/l	0.0 to .02
Rate of ortho-phosphate sedimentation	
Rate of ortho-phosphate re-suspension	

The next record defines the weir type code (if any) and of the height of the weir if present.

APPENDIX C

Table 1: Results for data from 1974.

Table 2: Results for data from 1975.

Table 3: Results for data from 1976.

Table 4: Results for data from 1989.

Table 1. Results of Climate Change Scenario Runs from Cookham to Teddington for 1974 data.

SITE: DATCHET		ORIGINAL	SCENARIO 1	%CHANGE	SCENARIO 2	%CHANGE	SCENARIO 3	%CHANGE	SCENARIO 4	%CHANGE
FLOW (cumecs)	Mean	61.56	65.27	6.02	58.37	-5.18	82.57	34.13	44.07	-28.42
	S.D.	53.13	56.80	6.90	50.56	-4.85	73.41	38.16	37.50	-29.42
	5%	13.56	13.95	2.88	12.77	-5.83	16.90	24.63	10.01	-26.18
	95%	172.48	183.49	6.38	164.39	-4.69	234.35	35.87	123.62	-28.33
	C.V.	1.16	1.15	-0.82	1.15	-0.35	1.12	-2.92	1.18	1.42
NITRATE (mg/l)	Mean	6.63	6.60	-0.45	6.59	-0.60	6.63	0.00	6.55	-1.21
	S.D.	2.28	2.29	0.44	2.28	0.00	2.28	0.00	2.28	0.00
	5%	5.10	5.05	-0.98	5.04	-1.18	5.10	0.00	4.94	-3.14
	95%	13.17	13.12	-0.38	13.10	-0.53	13.17	0.00	13.03	-1.06
	C.V.	2.91	2.88	-0.89	2.89	-0.60	2.91	0.00	2.87	-1.21
DO (mg/l)	Mean	9.90	9.06	-8.48	9.04	-8.69	9.52	-3.84	8.53	-13.84
	S.D.	1.64	2.30	40.24	2.39	45.73	1.72	4.88	3.11	89.63
	5%	7.52	5.10	-32.18	4.95	-34.18	7.19	-4.39	3.00	-60.11
	95%	12.67	12.70	0.24	12.98	2.45	12.34	-2.60	13.33	5.21
	C.V.	6.04	3.94	-34.75	3.78	-37.34	5.53	-8.31	2.74	-54.56
DO (% saturation)	Mean	91.07	86.83	-4.66	86.62	-4.89	90.28	-0.87	82.18	-9.76
	S.D.	16.49	20.21	22.56	21.25	28.87	15.53	-5.82	28.70	74.04
	5%	71.38	56.75	-20.50	55.69	-21.98	72.48	1.54	33.79	-52.66
	95%	123.36	129.18	4.72	131.63	6.70	123.56	0.16	139.44	13.04
	C.V.	5.52	4.30	-22.21	4.08	-26.19	5.81	5.26	2.86	-48.15
BOD (mg/l)	Mean	3.67	3.65	-0.54	3.60	-1.91	3.74	1.91	3.47	-5.45
	S.D.	2.19	2.18	-0.46	2.14	-2.28	2.25	2.74	2.03	-7.31
	5%	1.95	1.92	-1.54	1.87	-4.10	2.01	3.08	1.75	-10.26
	95%	9.49	9.43	-0.63	9.26	-2.42	9.77	2.95	8.92	-6.01
	C.V.	1.68	1.67	-0.09	1.68	0.38	1.66	-0.81	1.71	2.00
AMMONIA (mg/l)	Mean	0.16	0.16	0.00	0.16	0.00	0.17	6.25	0.15	-6.25
	S.D.	0.10	0.10	0.00	0.10	0.00	0.10	0.00	0.10	0.00
	5%	0.07	0.06	-14.29	0.06	-14.29	0.07	0.00	0.05	-28.57
	95%	0.42	0.41	-2.38	0.40	-4.76	0.43	2.38	0.38	-9.52
	C.V.	1.60	1.60	0.00	1.60	0.00	1.70	6.25	1.50	-6.25
TEMPERATURE (degrees celcius)	Mean	11.64	13.83	18.81	13.83	18.81	13.09	12.46	14.41	23.80
	S.D.	4.38	4.16	-5.02	4.16	-5.02	4.13	-5.71	4.15	-5.25
	5%	7.02	9.22	31.34	9.22	31.34	8.42	19.94	9.81	39.74
	95%	18.48	20.44	10.61	20.44	10.61	19.66	6.39	21.01	13.69
	C.V.	2.66	3.32	25.10	3.32	25.10	3.17	19.26	3.47	30.66
ORTHO-PHOSPHATE (mg/l)	Mean	0.75	0.75	0.00	0.74	-1.33	0.75	0.00	0.74	-1.33
	S.D.	0.28	0.28	0.00	0.27	-3.57	0.28	0.00	0.27	-3.57
	5%	0.36	0.36	0.00	0.36	0.00	0.36	0.00	0.36	0.00
	95%	1.16	1.17	0.86	1.16	0.00	1.19	2.59	1.13	-2.59
	C.V.	2.68	2.68	0.00	2.74	2.32	2.68	0.00	2.74	2.32

Table 1. (Continued).

SITE: EGHAM		ORIGINAL	SCENARIO 1	%CHANGE	SCENARIO 2	%CHANGE	SCENARIO 3	%CHANGE	SCENARIO 4	%CHANGE
FLOW (cumecs)	Mean	61.66	65.83	6.75	50.06	-18.82	85.38	38.46	41.94	-31.98
	S.D.	59.33	63.38	6.83	56.44	-4.86	82.05	38.30	42.01	-29.19
	5%	10.58	11.07	4.63	9.62	-9.07	14.71	39.04	6.19	-41.49
	95%	183.61	194.09	5.71	173.13	-5.71	258.87	40.99	133.12	-27.50
	C.V.	1.04	1.04	-0.07	0.89	-14.67	1.04	0.12	1.00	-3.95
NITRATE (mg/l)	Mean	6.73	6.69	-0.59	6.68	-0.74	6.73	0.00	6.63	-1.49
	S.D.	2.17	2.17	0.00	2.17	0.00	2.17	0.00	2.16	-0.46
	5%	5.27	5.20	-1.33	5.19	-1.52	5.26	-0.19	5.10	-3.23
	95%	12.92	12.89	-0.23	12.86	-0.46	12.94	0.15	12.76	-1.24
	C.V.	3.10	3.08	-0.59	3.08	-0.74	3.10	0.00	3.07	-1.03
DO (mg/l)	Mean	10.53	9.97	-5.32	10.03	-4.75	10.14	-3.70	9.96	-5.41
	S.D.	1.62	1.81	11.73	1.88	16.05	1.52	-6.17	2.14	32.10
	5%	8.29	7.58	-8.56	7.59	-8.44	8.12	-2.05	6.99	-15.68
	95%	13.51	13.58	0.52	13.94	3.18	13.01	-3.70	14.44	6.88
	C.V.	6.50	5.51	-15.26	5.34	-17.92	6.67	2.63	4.65	-28.40
DO (% saturation)	Mean	95.91	95.18	-0.76	95.76	-0.16	95.34	-0.59	96.20	0.30
	S.D.	17.80	17.89	0.51	18.84	5.84	15.57	-12.53	21.55	21.07
	5%	90.90	77.69	-14.53	77.84	-14.37	77.92	-14.28	74.79	-17.72
	95%	133.43	135.88	1.84	139.61	4.63	127.53	-4.42	150.00	12.42
	C.V.	5.39	5.32	-1.26	5.08	-5.67	6.12	13.64	4.46	-17.15
BOD (mg/l)	Mean	3.67	3.65	-0.54	3.62	-1.36	3.73	1.63	3.51	-4.36
	S.D.	2.01	1.99	-1.00	1.96	-2.49	2.05	1.99	1.88	-6.47
	5%	2.24	2.22	-0.89	2.18	-2.68	2.31	3.12	2.04	-8.93
	95%	9.00	8.92	-0.89	8.77	-2.56	9.16	1.78	8.49	-5.67
	C.V.	1.83	1.83	0.45	1.85	1.15	1.82	-0.35	1.87	2.25
AMMONIA (mg/l)	Mean	0.16	0.16	0.00	0.15	-6.25	0.16	0.00	0.14	-12.50
	S.D.	0.10	0.10	0.00	0.10	0.00	0.10	0.00	0.09	-10.00
	5%	0.06	0.06	0.00	0.06	0.00	0.06	0.00	0.05	-16.67
	95%	0.40	0.39	-2.50	0.38	-5.00	0.41	2.50	0.35	-12.50
	C.V.	1.60	1.60	0.00	1.50	-6.25	1.60	0.00	1.56	-2.78
TEMPERATURE (degrees celcius)	Mean	11.01	13.21	19.98	13.20	19.89	12.49	13.44	13.75	24.89
	S.D.	3.62	3.41	-5.80	3.40	-6.08	3.40	-6.08	3.35	-7.46
	5%	7.12	9.31	30.76	9.31	30.76	8.51	19.52	9.91	39.19
	95%	16.62	18.58	11.79	18.54	11.55	17.86	7.46	19.00	14.32
	C.V.	3.04	3.87	27.37	3.88	27.65	3.67	20.78	4.10	34.95
ORTHO-PHOSPHATE (mg/l)	Mean	0.90	0.90	0.00	0.91	1.11	0.90	0.00	0.92	2.22
	S.D.	0.32	0.32	0.00	0.32	0.00	0.32	0.00	0.33	3.13
	5%	0.44	0.44	0.00	0.44	0.00	0.44	0.00	0.44	0.00
	95%	1.44	1.43	-0.69	1.44	0.00	1.42	-1.39	1.48	2.78
	C.V.	2.81	2.81	0.00	2.84	1.11	2.81	0.00	2.79	-0.88

Table 1. (Continued).

SITE: TEDDINGTON		ORIGINAL	SCENARIO 1	%CHANGE	SCENARIO 2	%CHANGE	SCENARIO 3	%CHANGE	SCENARIO 4	%CHANGE
FLOW (cumecs)	Mean	79.94	84.66	5.90	73.97	-7.47	111.71	39.74	51.88	-35.10
	S.D.	82.08	87.56	6.68	78.12	-4.83	113.41	38.17	58.56	-28.66
	5%	12.21	13.09	7.21	10.51	-13.92	18.53	51.76	3.69	-69.78
	95%	258.04	273.00	5.80	243.08	-5.80	355.71	37.85	172.59	-33.12
	C.V.	0.97	0.97	-0.73	0.95	-2.78	0.99	1.14	0.89	-9.03
NITRATE (mg/l)	Mean	7.00	6.93	-1.00	6.93	-1.00	6.96	-0.57	6.94	-0.86
	S.D.	2.10	2.09	-0.48	2.11	0.48	2.08	-0.95	2.54	20.95
	5%	5.29	5.26	-0.57	5.26	-0.57	5.28	-0.19	4.78	-9.64
	95%	13.17	13.10	-0.53	13.07	-0.76	13.13	-0.30	13.07	-0.76
	C.V.	3.33	3.32	-0.53	3.28	-1.47	3.35	0.38	2.73	-18.03
DO (mg/l)	Mean	11.51	11.19	-2.78	11.26	-2.17	11.18	-2.87	11.24	-2.35
	S.D.	1.85	1.79	-3.24	1.85	0.00	1.73	-6.49	2.38	28.65
	5%	9.14	8.94	-2.19	8.93	-2.30	9.02	-1.31	8.66	-5.25
	95%	14.98	14.45	-3.54	14.80	-1.20	14.63	-2.34	15.23	1.67
	C.V.	6.22	6.25	0.48	6.09	-2.17	6.46	3.87	4.72	-24.09
DO (% saturation)	Mean	106.19	108.29	1.98	109.05	2.69	106.37	0.17	110.51	4.07
	S.D.	23.11	22.41	-3.03	23.06	-0.22	21.60	-6.53	27.97	21.03
	5%	84.29	86.79	2.97	86.76	2.93	85.70	1.67	86.02	2.05
	95%	150.00	150.00	0.00	150.00	0.00	150.00	0.00	150.00	0.00
	C.V.	4.59	4.83	5.16	4.73	2.92	4.92	7.17	3.95	-14.01
BOD (mg/l)	Mean	4.29	4.23	-1.40	4.26	-0.70	4.20	-2.10	4.47	4.20
	S.D.	1.68	1.64	-2.38	1.63	-2.98	1.67	-0.60	1.87	11.31
	5%	2.77	2.75	-0.72	2.73	-1.44	2.79	0.72	2.71	-2.17
	95%	8.55	8.43	-1.40	8.43	-1.40	8.53	-0.23	8.44	-1.29
	C.V.	2.55	2.58	1.01	2.61	2.35	2.51	-1.51	2.39	-6.39
AMMONIA (mg/l)	Mean	0.25	0.24	-4.00	0.24	-4.00	0.24	-4.00	0.26	4.00
	S.D.	0.08	0.07	-12.50	0.08	0.00	0.06	-25.00	0.25	213.50
	5%	0.11	0.11	0.00	0.11	0.00	0.11	0.00	0.10	-9.09
	95%	0.39	0.38	-2.56	0.37	-5.13	0.40	2.56	0.39	0.00
	C.V.	3.13	3.43	9.71	3.00	-4.00	4.00	28.00	1.04	-66.72
TEMPERATURE (degrees celcius)	Mean	11.36	13.48	18.66	13.50	18.84	12.74	12.15	14.17	24.74
	S.D.	3.91	3.66	-6.39	3.67	-6.14	3.62	-7.42	3.71	-5.12
	5%	7.22	9.61	33.10	9.62	33.24	8.82	22.16	10.22	41.55
	95%	17.21	19.06	10.75	19.06	10.75	18.30	6.33	19.74	14.70
	C.V.	2.91	3.68	26.77	3.68	26.61	3.52	21.13	3.82	31.46
ORTHO-PHOSPHATE (mg/l)	Mean	1.12	1.11	-0.89	1.12	0.00	1.10	-1.79	1.18	5.36
	S.D.	0.35	0.35	0.00	0.35	0.00	0.34	-2.86	0.46	31.43
	5%	0.54	0.54	0.00	0.54	0.00	0.54	0.00	0.55	1.85
	95%	1.63	1.62	-0.61	1.64	0.61	1.58	-3.07	1.77	8.59
	C.V.	3.20	3.17	-0.89	3.20	0.00	3.24	1.10	2.57	-19.84

Table 2. Results of Climate Change Scenario Runs from Cookham to Teddington for 1975 data.

SITE: DATCHET		ORIGINAL	SCENARIO 1	%CHANGE	SCENARIO 2	%CHANGE	SCENARIO 3	%CHANGE	SCENARIO 4	%CHANGE
FLOW (cumecs)	Mean	55.22	58.43	5.82	52.28	-5.32	72.31	30.94	39.58	-28.32
	S.D	56.42	60.10	6.52	53.51	-5.15	74.20	31.53	39.92	-29.24
	5%	13.35	13.98	4.72	12.64	-5.32	17.37	30.11	9.92	-25.69
	95%	184.48	198.27	7.48	176.21	-4.48	250.16	35.60	126.54	-31.41
	C.V.	0.98	0.97	-0.66	0.98	-0.17	0.97	-0.44	0.99	1.30
NITRATE (mg/l)	Mean	5.92	5.88	-0.68	5.86	-1.01	5.92	0.00	5.80	-2.03
	S.D	0.82	0.83	1.22	0.83	1.22	0.82	0.00	0.85	3.66
	5%	4.48	4.43	-1.12	4.41	-1.56	4.49	0.22	4.35	-2.90
	95%	7.22	7.17	-0.69	7.16	-0.83	7.19	-0.42	7.08	-1.94
	C.V.	7.22	7.08	-1.87	7.06	-2.21	7.22	0.00	6.82	-5.48
DO (mg/l)	Mean	10.41	9.26	-11.05	9.28	-10.85	9.57	-8.07	9.07	-12.87
	S.D	3.31	4.47	35.05	4.54	37.16	3.84	16.01	4.89	47.73
	5%	3.72	0.61	-83.60	0.60	-83.87	1.38	-62.90	0.32	-91.40
	95%	16.33	15.98	-2.14	16.10	-1.41	15.39	-5.76	16.16	-1.04
	C.V.	3.15	2.07	-34.13	2.04	-35.01	2.49	-20.76	1.85	-41.02
DO (% Saturation)	Mean	95.24	87.12	-8.53	87.30	-8.34	89.34	-6.19	86.02	-9.68
	S.D	29.72	41.44	39.43	42.22	42.06	34.67	16.66	46.37	56.02
	5%	42.21	7.21	-82.92	7.12	-83.13	16.19	-61.64	3.81	-90.97
	95%	150.00	150.00	0.00	150.00	0.00	144.69	-3.54	150.00	0.00
	C.V.	3.20	2.10	-34.40	2.07	-35.48	2.58	-19.59	1.86	-42.11
BOD (mg/l)	Mean	3.41	3.38	-0.88	3.35	-1.76	3.45	1.17	3.25	-4.69
	S.D	1.59	1.56	-1.89	1.55	-2.52	1.60	0.63	1.51	-5.03
	5%	1.41	1.40	-0.71	1.37	-2.84	1.46	3.55	1.30	-7.80
	95%	6.66	6.59	-1.05	6.53	-1.95	6.75	1.35	6.38	-4.20
	C.V.	2.14	2.17	1.03	2.16	0.78	2.16	0.54	2.15	0.36
AMMONIA (mg/l)	Mean	0.13	0.13	0.00	0.13	0.00	0.14	7.69	0.12	-7.69
	S.D	0.08	0.07	-12.50	0.07	-12.50	0.08	0.00	0.07	-12.50
	5%	0.05	0.04	-20.00	0.04	-20.00	0.05	0.00	0.03	-40.00
	95%	0.32	0.30	-6.25	0.29	-9.38	0.23	-28.12	0.27	-15.62
	C.V.	1.63	1.86	14.29	1.86	14.29	1.75	7.69	1.71	5.49
TEMPERATURE (degrees celcius)	Mean	12.02	14.17	17.89	14.17	17.89	13.45	11.90	14.73	22.55
	S.D	5.34	5.11	-4.31	5.11	-4.31	5.08	-4.87	5.11	-4.31
	5%	6.01	8.25	37.27	8.25	37.27	7.45	23.96	8.84	47.09
	95%	21.27	23.17	8.93	23.17	8.93	22.42	5.41	23.72	11.52
	C.V.	2.25	2.77	23.19	2.77	23.19	2.65	17.62	2.88	28.06
ORTHO-PHOSPHATE (mg/l)	Mean	0.72	0.72	0.00	0.72	0.00	0.73	1.39	0.72	0.00
	S.D	0.27	0.27	0.00	0.27	0.00	0.28	3.70	0.26	-3.70
	5%	0.41	0.41	0.00	0.41	0.00	0.41	0.00	0.42	2.44
	95%	1.06	1.07	0.94	1.06	0.00	1.08	1.89	1.04	-1.89
	C.V.	2.67	2.67	0.00	2.67	0.00	2.61	-2.23	2.77	3.85

Table 2. (Continued).

SITE: EGHAM		ORIGINAL	SCENARIO 1	%CHANGE	SCENARIO 2	%CHANGE	SCENARIO 3	%CHANGE	SCENARIO 4	%CHANGE
FLOW (cumecs)	Mean	57.35	61.12	6.57	53.87	-6.07	77.56	35.24	38.90	-32.18
	S.D	62.35	66.43	6.54	59.16	-5.11	81.91	31.37	44.18	-29.15
	5%	11.73	12.69	8.18	10.75	-8.35	17.66	50.55	6.91	-41.09
	95%	203.60	214.69	5.45	191.47	-5.96	271.28	33.24	137.36	-32.53
	C.V.	0.92	0.92	0.02	0.91	-1.01	0.95	2.95	0.88	-4.28
NITRATE (mg/l)	Mean	5.87	5.83	-0.68	5.81	-1.02	5.88	0.17	5.73	-2.39
	S.D	0.98	0.98	0.00	0.99	1.02	0.96	-2.04	1.02	4.08
	5%	4.38	4.32	-1.37	4.26	-2.74	4.43	1.14	4.13	-5.71
	95%	7.54	7.45	-1.19	7.43	-1.46	7.51	-0.40	7.32	-2.92
	C.V.	0.98	0.99	1.17	0.99	0.83	0.99	0.84	0.97	-0.73
DO (mg/l)	Mean	11.44	10.65	-6.91	10.77	-5.86	10.67	-6.73	10.75	-6.03
	S.D	2.50	3.02	20.80	3.11	24.40	2.52	0.80	3.44	37.60
	5%	7.39	5.18	-29.91	5.29	-28.42	5.90	-20.16	4.79	-35.18
	95%	16.53	16.20	-2.00	16.40	-0.79	15.34	-7.20	16.69	0.97
	C.V.	4.58	3.53	-22.94	3.46	-24.32	4.23	-7.47	3.13	-31.71
DO (% Saturation)	Mean	105.28	101.84	-3.27	103.12	-2.05	100.75	-4.30	104.12	-1.10
	S.D	25.21	27.37	8.57	28.52	13.13	22.67	-10.08	32.65	29.51
	5%	78.19	59.45	-23.97	60.09	-23.15	66.66	-14.75	55.51	-29.01
	95%	150.00	150.00	0.00	150.00	0.00	144.04	-3.97	150.00	0.00
	C.V.	4.18	3.72	-10.90	3.62	-13.42	4.44	6.42	3.19	-23.64
BOD (mg/l)	Mean	3.45	3.41	-1.16	3.41	-1.16	3.42	-0.87	3.40	-1.45
	S.D	1.30	1.27	-2.31	1.29	-0.77	1.26	-3.08	1.35	3.85
	5%	1.81	1.80	-0.55	1.80	-0.55	1.81	0.00	1.78	-1.66
	95%	6.00	5.89	-1.83	5.89	-1.83	5.96	-0.67	5.90	-1.67
	C.V.	2.65	2.69	1.18	2.64	-0.39	2.71	2.28	2.52	-5.10
AMMONIA (mg/l)	Mean	0.12	0.12	0.00	0.11	-8.33	0.12	0.00	0.10	-16.67
	S.D	0.08	0.08	0.00	0.07	-12.50	0.08	0.00	0.07	-12.50
	5%	0.03	0.02	-33.33	0.02	-33.33	0.03	0.00	0.02	-33.33
	95%	0.30	0.29	-3.33	0.28	-6.67	0.31	3.33	0.24	-20.00
	C.V.	1.50	1.50	0.00	1.57	4.76	1.50	0.00	1.43	-4.76
TEMPERATURE (degrees celcius)	Mean	11.65	13.81	18.54	13.80	18.45	13.09	12.36	14.35	23.18
	S.D	5.20	4.98	-4.23	4.98	-4.23	4.95	-4.81	4.97	-4.42
	5%	5.15	7.58	47.18	7.56	46.80	7.02	36.31	8.05	56.31
	95%	20.85	22.79	9.30	22.78	9.26	22.03	5.66	23.33	11.89
	C.V.	2.24	2.77	23.78	2.77	23.69	2.64	18.04	2.89	28.88
ORTHO-PHOSPHATE (mg/l)	Mean	0.86	0.86	0.00	0.87	1.16	0.85	-1.16	0.89	3.49
	S.D	0.32	0.32	0.00	0.32	0.00	0.31	-3.12	0.34	6.25
	5%	0.45	0.45	0.00	0.45	0.00	0.44	-2.22	0.45	0.00
	95%	1.35	1.34	-0.74	1.35	0.00	1.32	-2.22	1.41	4.44
	C.V.	2.69	2.69	0.00	2.72	1.16	2.74	2.03	2.62	-2.60

Table 2. (Continued).

SITE: TEDDINGTON

		ORIGINAL	SCENARIO 1	%CHANGE	SCENARIO 2	%CHANGE	SCENARIO 3	%CHANGE	SCENARIO 4	%CHANGE
FLOW (cumecs)	Mean	73.36	78.53	7.05	68.56	-6.54	101.31	38.11	47.96	-34.62
	S.D	80.80	86.09	6.55	76.75	-5.02	105.93	31.10	57.43	-28.93
	5%	14.39	16.11	11.95	12.76	-11.33	24.16	67.89	5.67	-60.60
	95%	256.20	274.40	7.10	242.27	-5.44	350.73	36.90	173.83	-32.15
	C.V.	0.91	0.91	0.47	0.89	-1.60	0.96	5.35	0.84	-8.00
NITRATE (mg/l)	Mean	6.35	6.27	-1.26	6.27	-1.26	6.29	-0.94	6.27	-1.26
	S.D	0.83	0.83	0.00	0.83	0.00	0.82	-1.20	1.07	28.92
	5%	5.17	5.05	-2.32	5.02	-2.90	5.16	-0.19	4.79	-7.35
	95%	7.72	7.62	-1.30	7.61	-1.42	7.75	0.39	7.56	-2.07
	C.V.	7.65	7.55	-1.26	7.55	-1.26	7.67	0.26	5.86	-23.41
DO (mg/l)	Mean	12.57	11.91	-5.25	11.94	-5.01	12.07	-3.98	11.68	-7.08
	S.D	2.50	2.90	16.00	2.93	17.20	2.63	5.20	3.30	32.00
	5%	9.49	8.36	-11.91	8.50	-10.43	8.92	-6.01	4.66	-50.90
	95%	17.78	17.00	-4.39	17.09	-3.88	17.00	-4.39	16.59	-6.69
	C.V.	5.03	4.11	-18.32	4.08	-18.95	4.59	-8.72	3.54	-29.61
DO (% Saturation)	Mean	105.28	114.73	8.98	115.10	9.33	114.57	8.82	114.20	8.47
	S.D	25.21	29.93	18.72	30.37	20.47	26.97	6.98	34.82	38.12
	5%	78.19	85.64	9.53	83.08	6.25	88.18	12.78	54.37	-30.46
	95%	150.00	150.00	0.00	150.00	0.00	150.00	0.00	150.00	0.00
	C.V.	4.18	3.83	-8.21	3.79	-9.25	4.25	1.72	3.28	-21.46
BOD (mg/l)	Mean	4.22	4.12	-2.37	4.23	0.24	3.93	-6.87	4.73	12.09
	S.D	1.72	1.63	-5.23	1.76	2.33	1.44	-16.28	2.37	37.79
	5%	2.38	2.37	-0.42	2.37	-0.42	2.36	-0.84	2.40	0.84
	95%	7.31	7.12	-2.60	7.34	0.41	6.78	-7.25	8.66	18.47
	C.V.	2.45	2.53	3.02	2.40	-2.04	2.73	11.24	2.00	-18.66
AMMONIA (mg/l)	Mean	0.25	0.23	-8.00	0.24	-4.00	0.23	-8.00	0.26	4.00
	S.D	0.15	0.14	-6.67	0.15	0.00	0.13	-13.33	0.24	60.00
	5%	0.10	0.09	-10.00	0.09	-10.00	0.09	-10.00	0.08	-20.00
	95%	0.69	0.64	-7.25	0.66	-4.35	0.61	-11.59	0.76	10.14
	C.V.	1.67	1.64	-1.43	1.60	-4.00	1.77	6.15	1.08	-35.00
TEMPERATURE (degrees celcius)	Mean	11.55	13.66	18.27	13.66	18.27	12.94	12.03	14.28	23.64
	S.D	5.12	4.89	-4.49	4.88	-4.69	4.88	-4.69	4.78	-6.64
	5%	5.20	7.71	48.27	7.74	48.85	7.01	34.81	8.42	61.92
	95%	20.47	22.36	9.23	22.31	8.99	21.67	5.86	22.71	10.94
	C.V.	2.26	2.79	23.83	2.80	24.08	2.65	17.54	2.99	32.43
ORTHO-PHOSPHATE (mg/l)	Mean	1.04	1.03	-0.96	1.04	0.00	1.03	-0.96	1.04	0.00
	S.D	0.33	0.33	0.00	0.33	0.00	0.33	0.00	0.34	3.03
	5%	0.54	0.54	0.00	0.55	1.85	0.54	0.00	0.55	1.85
	95%	1.45	1.46	0.69	1.44	-0.69	1.46	0.69	1.45	0.00
	C.V.	3.15	3.12	-0.96	3.15	0.00	3.12	-0.96	3.06	-2.94

Table 3. Results of Climate Change Scenario Runs from Cookham to Teddington for 1976 data.

SITE: DATCHET		ORIGINAL	SCENARIO 1	%CHANGE	SCENARIO 2	%CHANGE	SCENARIO 3	%CHANGE	SCENARIO 4	%CHANGE
FLOW (cumecs)	Mean	23.46	24.92	6.22	22.30	-4.98	31.53	34.39	16.74	-28.67
	S.D.	32.97	35.45	7.52	31.48	-4.50	45.10	36.82	22.64	-31.34
	5%	4.79	4.92	2.71	4.53	-5.43	5.92	23.59	3.60	-24.84
	95%	95.59	102.74	7.48	91.30	-4.49	129.87	35.86	65.60	-31.37
	C.V.	0.71	0.70	-1.21	0.71	-0.50	0.70	-1.78	0.74	3.89
NITRATE (mg/l)	Mean	7.56	7.46	-1.32	7.43	-1.72	7.57	0.13	7.30	-3.44
	S.D.	2.49	2.53	1.61	2.54	2.01	2.48	-0.40	2.60	4.42
	5%	4.72	4.56	-3.39	4.51	-4.45	4.78	1.27	4.28	-9.32
	95%	14.30	14.28	-0.14	14.26	-0.28	14.30	0.00	14.20	-0.70
	C.V.	3.04	2.95	-2.88	2.93	-3.65	3.05	0.54	2.81	-7.52
DO (mg/l)	Mean	10.77	9.43	-12.44	9.46	-12.16	9.85	-8.54	9.08	-15.69
	S.D.	4.54	5.11	12.56	5.16	13.66	4.81	5.95	5.29	16.52
	5%	0.27	0.04	-85.19	0.04	-85.19	0.09	-66.67	0.03	-88.89
	95%	15.86	15.49	-2.33	15.58	-1.77	15.44	-2.65	15.91	0.32
	C.V.	2.37	1.85	-22.21	1.83	-22.72	2.05	-13.68	1.72	-27.64
DO (% Saturation)	Mean	99.46	89.65	-9.86	89.91	-9.60	92.69	-6.81	87.07	-12.46
	S.D.	43.62	49.20	12.79	49.74	14.03	45.66	4.68	51.47	18.00
	5%	3.21	0.55	-82.87	0.55	-82.87	1.11	-65.42	0.34	-89.41
	95%	150.00	150.00	0.00	150.00	0.00	150.00	0.00	150.00	0.00
	C.V.	2.28	1.82	-20.09	1.81	-20.72	2.03	-10.97	1.69	-25.81
BOD (mg/l)	Mean	3.39	3.33	-1.77	3.29	-2.95	3.46	2.06	3.14	-7.37
	S.D.	1.07	1.06	-0.93	1.04	-2.80	1.09	1.87	1.01	-5.61
	5%	1.95	1.93	-1.03	1.92	-1.54	1.97	1.03	1.86	-4.62
	95%	6.15	6.05	-1.63	5.99	-2.60	6.19	0.65	5.80	-5.69
	C.V.	3.17	3.14	-0.84	3.16	-0.15	3.17	0.19	3.11	-1.87
AMMONIA (mg/l)	Mean	0.20	0.19	-5.00	0.19	-5.00	0.20	0.00	0.17	-15.00
	S.D.	0.13	0.13	0.00	0.13	0.00	0.13	0.00	0.12	-7.69
	5%	0.04	0.04	0.00	0.04	0.00	0.05	25.00	0.03	-25.00
	95%	0.49	0.46	-6.12	0.45	-8.16	0.48	-2.04	0.41	-16.33
	C.V.	1.54	1.46	-5.00	1.46	-5.00	1.54	0.00	1.42	-7.92
TEMPERATURE (degrees celcius)	Mean	13.01	15.07	15.83	15.07	15.83	14.39	10.61	15.59	19.83
	S.D.	6.39	6.06	-5.16	6.06	-5.16	6.03	-5.63	6.03	-5.63
	5%	3.51	6.38	81.77	6.38	81.77	5.79	64.96	6.97	98.58
	95%	23.68	25.46	7.52	25.43	7.39	24.79	4.69	25.87	9.25
	C.V.	2.04	2.49	22.14	2.49	22.14	2.39	17.21	2.59	26.98
ORTHO-PHOSPHATE (mg/l)	Mean	1.07	1.07	0.00	1.06	-0.93	1.09	1.87	1.04	-2.80
	S.D.	0.47	0.47	0.00	0.46	-2.13	0.49	4.26	0.44	-6.38
	5%	0.05	0.05	0.00	0.06	20.00	0.05	0.00	0.07	40.00
	95%	1.56	1.57	0.64	1.55	-0.64	1.59	1.92	1.52	-2.56
	C.V.	2.28	2.28	0.00	2.30	1.22	2.22	-2.29	2.36	3.82

Table 3. (Continued).

SITE: EGHAM		ORIGINAL	SCENARIO 1	%CHANGE	SCENARIO 2	%CHANGE	SCENARIO 3	%CHANGE	SCENARIO 4	%CHANGE
FLOW (cumecs)	Mean	20.00	21.72	8.60	18.60	-6.98	29.53	47.67	12.04	-39.82
	S.D.	34.82	37.51	7.73	33.26	-4.48	47.82	37.34	23.74	-31.82
	5%	5.07	5.38	6.11	4.54	-10.45	6.92	36.49	1.96	-61.34
	95%	97.26	105.08	8.04	92.57	-4.82	134.76	38.56	64.45	-33.73
	C.V.	0.57	0.58	0.80	0.56	-2.61	0.62	7.52	0.51	-11.74
NITRATE (mg/l)	Mean	7.20	7.10	-1.39	7.05	-2.08	7.22	0.28	6.87	-4.58
	S.D.	2.56	2.60	1.56	2.61	1.95	2.55	-0.39	2.64	3.13
	5%	4.08	3.91	-4.17	3.84	-5.88	4.12	0.98	3.61	-11.52
	95%	13.54	13.50	-0.30	13.48	-0.44	13.56	0.15	13.35	-1.40
	C.V.	2.81	2.73	-2.91	2.70	-3.96	2.83	0.67	2.60	-7.47
DO (mg/l)	Mean	12.72	11.95	-6.05	12.08	-5.03	11.98	-5.82	12.16	-4.40
	S.D.	2.49	2.81	12.85	2.82	13.25	2.66	6.83	2.94	18.07
	5%	8.81	6.81	-22.70	7.05	-19.98	7.15	-18.84	6.60	-25.09
	95%	16.31	15.84	-2.88	16.06	-1.53	15.86	-2.76	16.14	-1.04
	C.V.	5.11	4.25	-16.75	4.28	-16.14	4.50	-11.84	4.14	-19.03
DO (% Saturation)	Mean	120.78	119.38	-1.16	120.31	-0.39	118.03	-2.28	122.28	1.24
	S.D.	25.52	26.91	5.45	26.89	5.37	25.20	-1.25	28.62	12.15
	5%	89.81	82.87	-7.73	85.57	-4.72	84.55	-5.86	79.67	-11.29
	95%	150.00	150.00	0.00	150.00	0.00	150.00	0.00	150.00	0.00
	C.V.	4.73	4.44	-6.26	4.47	-5.46	4.68	-1.04	4.27	-9.72
BOD (mg/l)	Mean	3.75	3.76	0.27	3.69	-1.60	3.69	-1.60	3.75	0.00
	S.D.	1.33	1.28	-3.76	1.32	-0.75	1.25	-6.02	1.45	9.02
	5%	1.94	1.91	-1.55	1.90	-2.06	1.95	0.52	1.81	-6.70
	95%	7.06	6.90	-2.27	7.01	-0.71	6.79	-3.82	7.34	3.97
	C.V.	2.82	2.94	4.18	2.80	-0.85	2.95	4.70	2.59	-8.28
AMMONIA (mg/l)	Mean	0.18	0.17	-5.56	0.17	-5.56	0.18	0.00	0.15	-16.67
	S.D.	0.12	0.11	-8.33	0.11	-8.33	0.12	0.00	0.10	-16.67
	5%	0.05	0.04	-20.00	0.04	-20.00	0.04	-20.00	0.04	-20.00
	95%	0.39	0.37	-5.13	0.37	-5.13	0.41	5.13	0.35	-10.26
	C.V.	1.50	1.55	3.03	1.55	3.03	1.50	0.00	1.50	-0.00
TEMPERATURE (degrees celcius)	Mean	11.83	13.91	17.58	13.90	17.50	13.23	11.83	14.43	21.98
	S.D.	4.97	4.65	-6.44	4.64	-6.64	4.63	-6.84	4.59	-7.65
	5%	4.04	6.89	70.54	6.89	70.54	6.29	55.6º	7.49	85.40
	95%	20.24	22.01	8.75	22.01	8.75	21.29	5.19	22.50	11.17
	C.V.	2.38	2.99	25.67	3.00	25.85	2.86	20.05	3.14	32.08
ORTHO-PHOSPHATE (mg/l)	Mean	1.33	1.32	-0.75	1.34	0.75	1.30	-2.26	1.43	7.52
	S.D.	0.46	0.46	0.00	0.46	0.00	0.47	2.17	0.48	4.35
	5%	0.28	0.28	0.00	0.28	0.00	0.26	-7.14	0.30	7.14
	95%	1.89	1.87	-1.06	1.91	1.06	1.85	-2.12	2.08	10.05
	C.V.	2.89	2.87	-0.75	2.91	0.75	2.77	-4.34	2.98	3.04

Table 3. (Continued).

SITE: TEDDINGTON		ORIGINAL	SCENARIO 1	%CHANGE	SCENARIO 2	%CHANGE	SCENARIO 3	%CHANGE	SCENARIO 4	%CHANGE
FLOW (cumecs)	Mean	23.61	26.11	10.59	21.53	-8.80	37.61	59.32	12.52	-46.98
	S.D.	45.22	48.69	7.67	43.24	-4.38	61.98	37.07	30.84	-31.81
	5%	4.61	5.20	12.80	3.93	-14.75	7.80	69.20	0.80	-82.65
	95%	118.39	128.33	8.40	112.43	-5.03	166.06	40.27	76.69	-35.22
	C.V.	0.52	0.54	2.71	0.50	-4.63	0.61	16.24	0.41	-22.24
NITRATE (mg/l)	Mean	7.97	7.80	-2.13	7.81	-2.01	7.85	-1.51	7.62	-4.39
	S.D.	1.97	2.00	1.52	2.04	3.55	1.94	-1.52	2.49	26.40
	5%	5.20	5.01	-3.65	4.89	-5.96	5.22	0.38	3.50	-32.69
	95%	12.31	12.26	-0.41	12.21	-0.81	12.36	0.41	12.20	-0.89
	C.V.	4.05	3.90	-3.60	3.83	-5.37	4.05	0.02	3.06	-24.36
DO (mg/l)	Mean	13.48	13.07	-3.04	13.11	-2.74	13.17	-2.30	12.55	-6.90
	S.D.	2.14	1.99	-7.01	2.06	-3.74	2.04	-4.67	2.87	34.11
	5%	10.32	10.01	-3.00	9.81	-4.94	10.36	0.39	6.74	-34.69
	95%	17.05	16.42	-3.70	16.42	-3.70	16.52	-3.11	16.16	-5.22
	C.V.	6.30	6.57	4.27	6.36	1.03	6.46	2.49	4.37	-30.58
DO (% Saturation)	Mean	128.07	129.59	1.19	130.13	1.61	128.55	0.37	127.46	-0.48
	S.D.	27.30	25.52	-6.52	26.17	-4.14	25.70	-5.86	33.04	21.03
	5%	86.64	90.13	4.03	88.02	1.59	91.59	5.71	67.46	-22.14
	95%	150.00	150.00	0.00	150.00	0.00	150.00	0.00	150.00	0.00
	C.V.	4.69	5.08	8.24	4.97	6.00	5.00	6.62	3.86	-17.77
BOD (mg/l)	Mean	5.79	5.55	-4.15	5.86	1.21	5.16	-10.88	7.18	24.01
	S.D.	2.78	2.64	-5.04	2.88	3.60	2.31	-16.91	4.01	44.24
	5%	2.84	2.75	-3.17	2.83	-0.35	2.70	-4.93	3.15	10.92
	95%	9.24	8.92	-3.46	9.32	0.87	8.47	-8.33	11.55	25.00
	C.V.	2.08	2.10	0.94	2.03	-2.31	2.23	7.25	1.79	-14.03
AMMONIA (mg/l)	Mean	0.38	0.35	-7.89	0.37	-2.63	0.34	-10.53	0.41	7.89
	S.D.	0.18	0.16	-11.11	0.18	0.00	0.15	-16.67	0.24	33.33
	5%	0.17	0.15	-11.76	0.16	-5.88	0.16	-5.88	0.14	-17.65
	95%	0.71	0.65	-8.45	0.69	-2.82	0.59	-16.90	0.85	19.72
	C.V.	2.11	2.19	3.62	2.06	-2.63	2.27	7.37	1.71	-19.08
TEMPERATURE (degrees celcius)	Mean	12.35	14.24	15.30	14.28	15.63	13.52	9.47	15.33	24.13
	S.D.	5.01	4.64	-7.39	4.62	-7.78	4.64	-7.39	4.56	-8.98
	5%	4.39	7.21	64.24	7.21	64.24	6.60	50.34	7.83	78.36
	95%	19.80	21.39	8.03	21.32	7.68	20.87	5.40	21.43	8.23
	C.V.	2.47	3.07	24.50	3.09	25.39	2.91	18.20	3.36	36.38
ORTHO-PHOSPHATE (mg/l)	Mean	1.48	1.48	0.00	1.48	0.00	1.49	0.68	1.52	2.70
	S.D.	0.39	0.40	2.56	0.39	0.00	0.41	5.13	0.42	7.69
	5%	0.70	0.70	0.00	0.71	1.43	0.68	-2.86	0.69	-1.43
	95%	2.02	2.02	0.00	2.01	-0.50	2.05	1.49	2.04	0.99
	C.V.	3.79	3.70	-2.50	3.79	0.00	3.63	-4.24	3.62	-4.63

Table 4. Results of Climate Change Scenario Runs from Cookham to Teddington for 1989 data.

SITE: DATCHET		ORIGINAL	SCENARIO 1	%CHANGE	SCENARIO 2	%CHANGE	SCENARIO 3	%CHANGE	SCENARIO 4	%CHANGE
FLOW (cumecs)	Mean	44.90	47.46	5.71	42.51	-5.33	58.87	31.13	32.26	-28.14
	S.D.	43.89	46.94	6.94	41.73	-4.92	58.37	33.00	30.69	-30.07
	5%	14.73	15.25	3.53	12.95	-12.08	18.82	27.77	10.93	-25.80
	95%	149.59	158.80	6.16	142.22	-4.93	191.23	27.84	106.91	-28.53
	C.V.	1.02	1.01	-1.15	1.02	-0.43	1.01	-1.41	1.05	2.75
NITRATE (mg/l)	Mean	6.52	6.47	-0.77	6.45	-1.07	6.53	0.15	6.36	-2.45
	S.D.	1.19	1.21	1.68	1.22	2.52	1.19	0.00	1.25	5.04
	5%	4.59	4.50	-1.96	4.46	-2.83	4.61	0.44	4.29	-6.54
	95%	7.96	7.94	-0.25	7.94	-0.25	7.96	0.00	7.92	-0.50
	C.V.	5.48	5.35	-2.41	5.29	-3.51	5.49	0.15	5.09	-7.14
DO (mg/l)	Mean	10.08	9.00	-10.71	9.01	-10.62	9.42	-6.55	8.52	-15.48
	S.D.	2.83	3.33	17.67	3.38	19.43	3.04	7.42	3.65	28.98
	5%	1.58	0.23	-85.44	0.23	-85.44	0.54	-65.82	0.12	-92.41
	95%	12.91	12.95	0.31	13.21	2.32	12.50	-3.18	13.93	7.90
	C.V.	3.56	2.70	-24.12	2.67	-25.16	3.10	-13.00	2.33	-34.47
DO (% Saturation)	Mean	95.43	88.29	-7.48	88.49	-7.27	91.44	-4.18	84.27	-11.69
	S.D.	28.91	32.64	12.90	33.26	15.05	29.77	2.97	35.96	24.39
	5%	18.31	2.81	-84.65	2.74	-85.04	6.44	-64.83	1.45	-92.08
	95%	131.77	132.59	0.62	135.78	3.04	125.68	-4.62	141.08	7.07
	C.V.	3.30	2.70	-18.05	2.66	-19.40	3.07	-6.95	2.34	-29.01
BOD (mg/l)	Mean	2.39	2.36	-1.26	2.36	-1.26	2.38	-0.42	2.34	-2.09
	S.D.	1.06	1.04	-1.89	1.01	-4.72	1.10	3.77	0.94	-11.32
	5%	1.28	1.27	-0.78	1.27	-0.78	1.26	-1.56	1.26	-1.56
	95%	4.80	4.71	-1.88	4.60	-4.17	4.97	3.54	4.24	-11.67
	C.V.	2.25	2.27	0.64	2.34	3.63	2.16	-4.04	2.49	10.41
AMMONIA (mg/l)	Mean	0.18	0.18	0.00	0.17	-5.56	0.19	5.56	0.16	-11.11
	S.D.	0.11	0.11	0.00	0.11	0.00	0.11	0.00	0.10	-9.09
	5%	0.07	0.07	0.00	0.07	0.00	0.07	0.00	0.07	0.00
	95%	0.46	0.45	-2.17	0.45	-2.17	0.46	0.00	0.43	-6.52
	C.V.	1.64	1.64	0.00	1.55	-5.56	1.73	5.56	1.60	-2.22
TEMPERATURE (degrees celsius)	Mean	13.29	15.47	16.40	15.47	16.40	14.73	10.84	16.05	20.77
	S.D.	4.96	4.71	-5.04	4.71	-5.04	4.67	-5.85	4.71	-5.04
	5%	6.08	8.93	46.88	8.93	46.88	8.35	37.34	9.53	56.74
	95%	22.14	24.09	8.81	24.09	8.81	23.32	5.33	24.65	11.34
	C.V.	2.68	3.28	22.58	3.28	22.58	3.15	17.72	3.41	27.18
ORTHO-PHOSPHATE (mg/l)	Mean	1.86	1.86	0.00	1.85	-0.54	1.89	1.61	1.81	-2.69
	S.D.	0.21	0.21	0.00	0.21	0.00	0.23	9.52	0.20	-4.76
	5%	1.70	1.71	0.59	1.70	0.00	1.72	1.18	1.67	-1.76
	95%	2.14	2.15	0.47	2.13	-0.47	2.21	3.27	2.07	-3.27
	C.V.	8.86	8.86	0.00	8.81	-0.54	8.22	-7.22	9.05	2.18

Table 4. (Continued).

SITE: EGHAM		ORIGINAL	SCENARIO 1	%CHANGE	SCENARIO 2	%CHANGE	SCENARIO 3	%CHANGE	SCENARIO 4	%CHANGE
FLOW (cumecs)	Mean	38.37	41.03	6.94	35.87	-6.51	52.93	37.96	25.21	-34.31
	S.D.	42.38	45.42	7.18	40.19	-5.16	56.85	34.16	29.22	-31.06
	5%	9.78	10.59	8.28	8.65	-11.55	15.61	59.61	4.38	-55.21
	95%	139.78	148.82	6.47	130.47	-6.66	182.36	30.46	93.03	-33.45
	C.V.	0.91	0.90	-0.22	0.89	-1.42	0.93	2.83	0.86	-4.72
NITRATE (mg/l)	Mean	6.34	6.28	-0.95	6.25	-1.42	6.37	0.47	6.11	-3.63
	S.D.	1.27	1.29	1.57	1.31	3.15	1.26	-0.79	1.36	7.09
	5%	4.32	4.22	-2.31	4.16	-3.70	4.37	1.16	3.97	-8.10
	95%	7.95	7.93	-0.25	7.92	-0.38	7.96	0.13	7.89	-0.75
	C.V.	4.99	4.87	-2.48	4.77	-4.43	5.06	1.27	4.49	-10.01
DO (mg/l)	Mean	11.17	10.26	-8.15	10.38	-7.07	10.39	-6.98	10.29	-7.88
	S.D.	2.34	2.89	23.50	2.96	26.50	2.52	7.69	3.20	36.75
	5%	6.30	2.70	-57.14	2.72	-56.83	4.04	-35.87	1.75	-72.22
	95%	14.25	13.92	-2.32	14.10	-1.05	13.21	-7.30	14.06	-1.33
	C.V.	4.77	3.55	-25.63	3.51	-26.54	4.12	-13.63	3.22	-32.64
DO (% Saturation)	Mean	107.21	102.31	-4.57	103.65	-3.32	102.17	-4.70	104.04	-2.96
	S.D.	27.67	31.17	12.65	32.45	17.28	27.00	-2.42	35.40	27.94
	5%	72.49	32.44	-55.25	32.63	-54.99	47.54	-34.42	21.26	-70.67
	95%	150.00	149.92	-0.05	150.00	0.00	140.51	-6.33	150.00	0.00
	C.V.	3.87	3.28	-15.29	3.19	-17.56	3.78	-2.34	2.94	-24.15
BOD (mg/l)	Mean	2.55	2.50	-1.96	2.52	-1.18	2.47	-3.14	2.60	1.96
	S.D.	1.05	1.02	-2.86	1.02	-2.86	1.05	0.00	1.02	-2.86
	5%	1.34	1.32	-1.49	1.33	-0.75	1.33	-0.75	1.33	-0.75
	95%	4.56	4.45	-2.41	4.42	-3.07	4.63	1.54	4.32	-5.26
	C.V.	2.43	2.45	0.92	2.47	1.73	2.35	-3.14	2.55	4.96
AMMONIA (mg/l)	Mean	0.17	0.16	-5.88	0.16	-5.88	0.17	0.00	0.15	-11.76
	S.D.	0.11	0.11	0.00	0.11	0.00	0.11	0.00	0.10	-9.09
	5%	0.06	0.06	0.00	0.06	0.00	0.06	0.00	0.05	-16.67
	95%	0.43	0.42	-2.33	0.41	-4.65	0.45	4.65	0.36	-16.28
	C.V.	1.55	1.45	-5.88	1.45	-5.88	1.55	0.00	1.50	-2.94
TEMPERATURE (degrees celcius)	Mean	13.31	15.48	16.30	15.48	16.30	14.75	10.82	16.03	20.44
	S.D.	4.99	4.74	-5.01	4.74	-5.01	4.69	-6.01	4.76	-4.61
	5%	6.20	9.06	46.13	9.06	46.13	8.46	36.45	9.64	55.48
	95%	22.05	23.99	8.80	23.98	8.75	23.23	5.35	24.50	11.11
	C.V.	2.67	3.27	22.44	3.27	22.44	3.14	17.91	3.37	26.26
ORTHO-PHOSPHATE (mg/l)	Mean	2.00	2.00	0.00	2.00	0.00	2.00	0.00	2.04	2.00
	S.D.	0.26	0.26	0.00	0.26	0.00	0.26	0.00	0.30	15.38
	5%	1.72	1.72	0.00	1.72	0.00	1.72	0.00	1.72	0.00
	95%	2.40	2.40	0.00	2.40	0.00	2.40	0.00	2.54	5.83
	C.V.	7.69	7.69	0.00	7.69	0.00	7.69	0.00	6.80	-11.60

Table 4. (Continued).

SITE: TEDDINGTON		ORIGINAL	SCENARIO 1	%CHANGE	SCENARIO 2	%CHANGE	SCENARIO 3	%CHANGE	SCENARIO 4	%CHANGE
FLOW (cumecs)	Mean	38.54	41.86	8.60	35.43	-8.08	56.74	47.22	22.47	-41.71
	S.D.	51.41	55.10	7.18	48.77	-5.13	68.90	34.01	35.27	-31.40
	5%	5.95	7.05	18.49	4.40	-26.05	13.82	132.27	0.97	-83.70
	95%	161.11	176.14	9.33	152.10	-5.59	218.51	35.63	102.25	-36.53
	C.V.	0.75	0.76	1.33	0.73	-3.11	0.82	9.86	0.64	-15.03
NITRATE (mg/l)	Mean	6.55	6.45	-1.53	6.41	-2.14	6.57	0.31	6.47	-1.22
	S.D.	1.08	1.10	1.85	1.14	5.56	1.06	-1.85	2.16	100.00
	5%	4.81	4.66	-3.12	4.58	-4.78	4.85	0.83	4.13	-14.14
	95%	8.05	8.01	-0.50	8.01	-0.50	8.05	0.00	9.48	17.76
	C.V.	6.06	5.86	-3.32	5.62	-7.29	6.20	2.20	3.00	-50.61
DO (mg/l)	Mean	12.13	11.25	-7.25	11.26	-7.17	11.50	-5.19	10.41	-14.18
	S.D.	1.92	2.74	42.71	2.86	48.96	2.29	19.27	3.98	107.29
	5%	9.45	5.17	-45.29	5.05	-46.56	8.06	-14.71	1.27	-86.56
	95%	14.79	14.25	-3.65	14.60	-1.28	14.45	-2.30	14.46	-2.23
	C.V.	6.32	4.11	-35.01	3.94	-37.68	5.02	-20.51	2.62	-58.60
DO (% Saturation)	Mean	117.62	112.90	-4.01	113.16	-3.79	114.00	-3.08	106.33	-9.60
	S.D.	28.24	32.48	15.01	33.75	19.51	28.64	1.42	44.67	58.18
	5%	81.96	61.48	-24.99	60.14	-26.62	85.44	4.25	12.15	-85.18
	95%	150.00	150.00	0.00	150.00	0.00	150.00	0.00	150.00	0.00
	C.V.	4.17	3.48	-16.54	3.35	-19.50	3.98	-4.43	2.38	-42.85
BOD (mg/l)	Mean	3.22	3.10	-3.73	3.23	0.31	2.94	-8.70	3.86	19.88
	S.D.	1.22	1.15	-5.74	1.23	0.82	1.07	-12.30	1.56	27.87
	5%	1.87	1.83	-2.14	1.87	0.00	1.67	-10.70	1.96	4.81
	95%	5.22	5.06	-3.07	5.29	1.34	4.74	-9.20	6.31	20.88
	C.V.	2.64	2.70	2.13	2.63	-0.50	2.75	4.10	2.47	-6.25
AMMONIA (mg/l)	Mean	0.46	0.42	-8.70	0.45	-2.17	0.40	-13.04	0.75	63.04
	S.D.	0.24	0.21	-12.50	0.24	0.00	0.20	-16.67	1.31	445.83
	5%	0.12	0.11	-8.33	0.11	-8.33	0.11	-8.33	0.12	0.00
	95%	0.92	0.84	-8.70	0.90	-2.17	0.77	-16.30	1.69	83.70
	C.V.	1.92	2.00	4.35	1.88	-2.17	2.00	4.35	0.57	-70.13
TEMPERATURE (degrees celcius)	Mean	13.28	15.30	15.21	15.29	15.14	14.61	10.02	15.52	16.87
	S.D.	5.03	4.73	-5.96	4.74	-5.77	4.69	-6.76	4.98	-0.99
	5%	6.34	9.09	43.38	9.03	42.43	8.51	34.23	7.73	21.92
	95%	21.74	23.52	8.19	23.47	7.96	22.85	5.11	23.23	6.85
	C.V.	2.64	3.23	22.52	3.23	22.18	3.12	17.99	3.12	18.04
ORTHO-PHOSPHATE (mg/l)	Mean	2.30	2.28	-0.87	2.32	0.87	2.27	-1.30	2.50	8.70
	S.D.	0.42	0.37	-11.90	0.47	11.90	0.35	-16.67	0.78	85.71
	5%	1.71	1.71	0.00	1.71	0.00	1.71	0.00	1.70	-0.58
	95%	2.88	2.83	-1.74	2.95	2.43	2.84	-1.39	3.74	29.86
	C.V.	5.48	6.16	12.53	4.94	-9.86	6.49	18.43	3.21	-41.47